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Petrographic and Salinity Characteristics of Brackish Water Ice in the Bay of Bothnia

Anthony J. Gow, W.F. Weeks, Pekka Kosloff and Susan Carsey

July 1992

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Abstract

Field observations made during the March 1988 BEPERS (Bothnian Experiment in Preparation for ERS-1) remote sensing experiment included measurements of the snow and ice thickness, temperature, salinity and crystal structure profiles of the different types of brackish ice that form in the Bay of Bothnia. Both undeformed fast ice and ice that had formed under more disturbed conditions were sampled. Ice thicknesses varied from 36 to 64 cm in the bay to the east of Umeå, Sweden, with somewhat thicker ice (76 cm) occurring in the northernmost, nearly fresh water areas of the Bay of Bothnia. Three major ice crystal types or textures were identified—granular, transition and columnar ice—with the amount of each depending on the level of disturbance in the water column. At seven of the sixteen sites investigated, granular (mainly frazil) ice was the dominant component. At six of the remaining nine sites, columnar–congelation ice was the predominant ice crystal type. A mix of transition and transition–congelation ice types dominated the structure of the remaining three sites. At all but two sites the bottom ice consisted of congelation ice, which in many instances exhibited the ice plate and brine layer substructure so typical of arctic sea ice. A variety of c-axis fabrics were observed in the columnar–congelation ice, including random, vertical and horizontal (planar) orientations. Aligned c-axes were observed at several locations, but in most cases there was no obvious pattern to the geographic arrangement of these fabrics. Surface water salinities ranged from 3.6 to 4.1‰ except at the northernmost sites near Tornio, where essentially riverine fresh water was present. Bulk salinities ranged from 1.21–0.58‰ in the area of the main experiment to as low as 0.06‰ near Tornio. Ice temperatures were usually higher than –3.5°C. Brine volume profiles were used to estimate representative ice property profiles for comparison with those of more typical sea ice of similar thicknesses from the Arctic Ocean. A variety of structural factors contributing to specific areas of high and low radar return in the Bay of Bothnia are also discussed.

Cover: Swedish icebreaker Tor *breaking track in ice for* Aranda.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, *Metric Practice Guide*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

CRREL Report 92-13

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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PREFACE

This report was prepared by Dr. Anthony J. Gow, Research Geologist, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory; Dr. Wilford F. Weeks, Geophysical Institute, University of Alaska, Fairbanks; Pekka Kosloff, Finnish Institute of Marine Research, Helsinki, Finland; and Susan Carsey,* Radarsat Project Office, Ottawa, Canada. This work was performed as part of the Bothnian Experiment in Preparation for ERS-1 (BEPERS). The participation of Dr. Gow and Dr. Weeks was funded by the Oceanic Processes Branch, NASA, and by the Office of Naval Research (ONR) under contracts N0001488WM24022 and N0001488WM24015. The report was reviewed technically by Dr. Debra Meese and Stephen Ackley.

The authors thank the members of the BEPERS Organizing Committee for permitting them to participate in their experiment. They are especially indebted to Dr. Matti Leppäranta, Dr. Erkki Palosuo, the staffs of the Finnish Institute of Marine Research and the Technical Research Center of Finland, and members of the Finnish Coast Guard for their support of the program.

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CONTENTS

ILLUSTRATIONS

Figure

TABLES

Table

Petrographic and Salinity Characteristics of Brackish Water Ice in the Bay of Bothnia

ANTHONY J. GOW, W.F. WEEKS, PEKKA KOSLOFF AND SUSAN CARSEY

INTRODUCTION

The Bothnian Experiment in Preparation for ERS-1, better known as BEPERS, was a major component in the Finnish and Swedish preparations for the launch of the first European microwave satellite (ERS-1) in 1991. The objective of the March 1988 field program (generally referred to as BEPERS'88) was to produce sea ice remote sensing data similar to that which will be obtained by ERS-1 together with high-quality ground truth in support of the remote sensing observations. These data are now being used for developing algorithms that will process and extract geophysically meaningful information from SAR (synthetic aperture radar) images of sea ice needed to evaluate the potential of SAR in operational sea ice mapping and forecasting using numerical models and in planning calibration and validation experiments in the Baltic Sea. Also, the BEPERS'88 data set will undoubtedly prove valuable in designing future investigations of other brackish ice areas.

The BEPERS'88 program involved scientists from seven countries and used three ships and several aircraft, including a Convair 580 from the Canadian Center for Remote Sensing, which was equipped with a multifrequency SAR imaging system. The purpose of this report is to present results of measurements of the major physical, thermal and structural characteristics of different types of brackish ice encountered in the Bay of Bothnia during BEPERS'88. These data are combined with the results of earlier observational programs to provide a picture of the intrinsic nature of the ice that forms in the Bay of Bothnia and to compare the properties of this ice with those of typical arctic sea ice.

PHYSICAL SETTING

The Baltic Sea is characterized by a narrow, shallow connection (sill depth of 18 m) with the North Sea and a division into a number of basins and bays (Fig. 1). The northernmost portions of the Baltic are the Sea of Bothnia and finally the Bay of Bothnia, which is separated by a sill of 25 m between the coastal cities of Umeå, Sweden, and

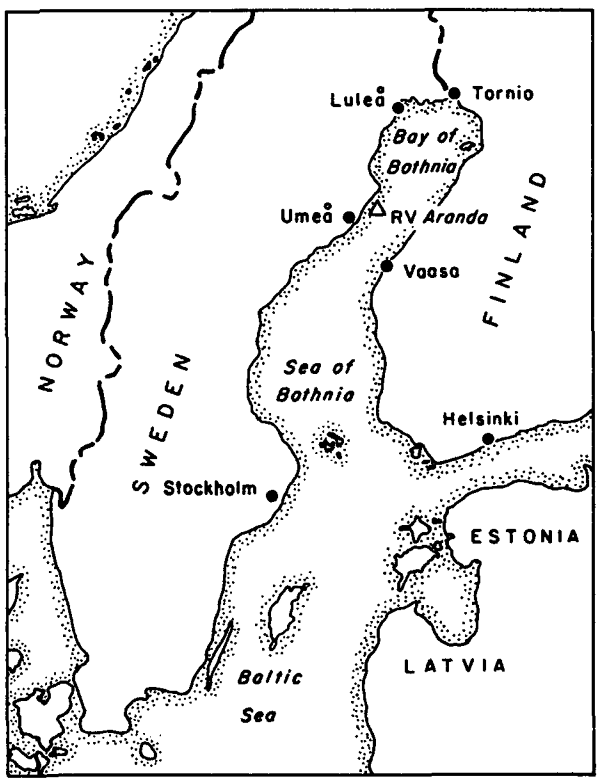


Figure 1. Location of the BEPERS'88 program.

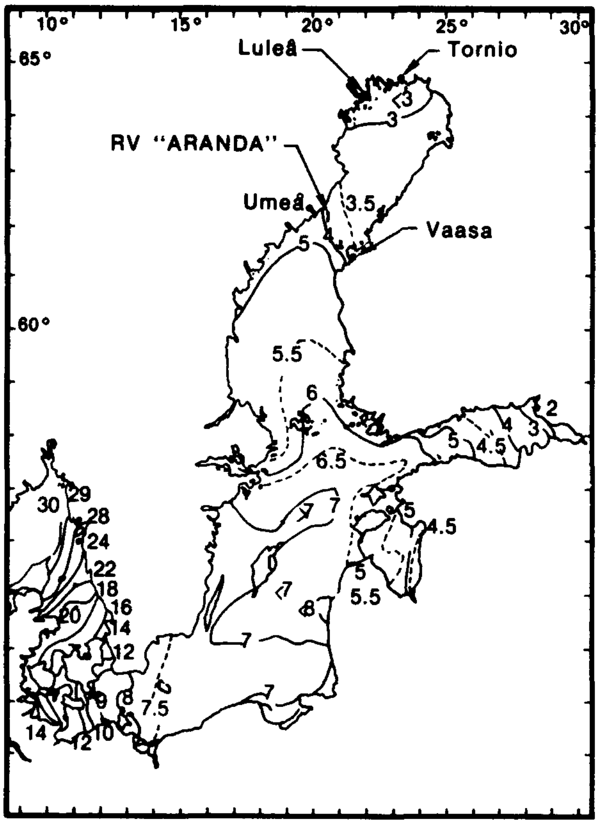


Figure 2. Map of mean sea surface salinity (‰) in the Baltic in November. (After Bock 1971.)

Vaasa, Finland. The salinity of the Baltic is controlled by a balance between the inflows of saline water from the North Sea and fresh water from the rivers of the region. As might be expected, the greater the distance from the North Sea proper, the lower the salinity. Figure 2 shows the mean surface salinity in the Baltic during November (Bock 1971) and clearly demonstrates this fact. In the Bay of Bothnia, surface salinities are shown to vary from 4‰ in the south to less than 3‰ in the north. In fact, as will be shown, surface salinities in the northern portions of the bay are significantly less than 1‰. Maps similar to Figure 2 apparently do not exist for the March time period of the BEPERS'88 program. However, the water salinity values at our sampling sites were in general agreement with the contours shown in Figure 2.

Ice formation starts in the northernmost portions of the Bay of Bothnia in late October, with the ice cover extending southward as air temperatures decrease. During an average year, ice covers the bay by mid-January and the Sea of Bothnia by mid-February (Thompson and Leppäranta 1987), with the extent of the ice cover varying considerably from year to year. Because there are numerous near-shore islands in some regions of the bay, fast ice develops early during the ice growth period along many regions of the coast, where it is stable for the remainder of the winter (Leppäranta 1981).

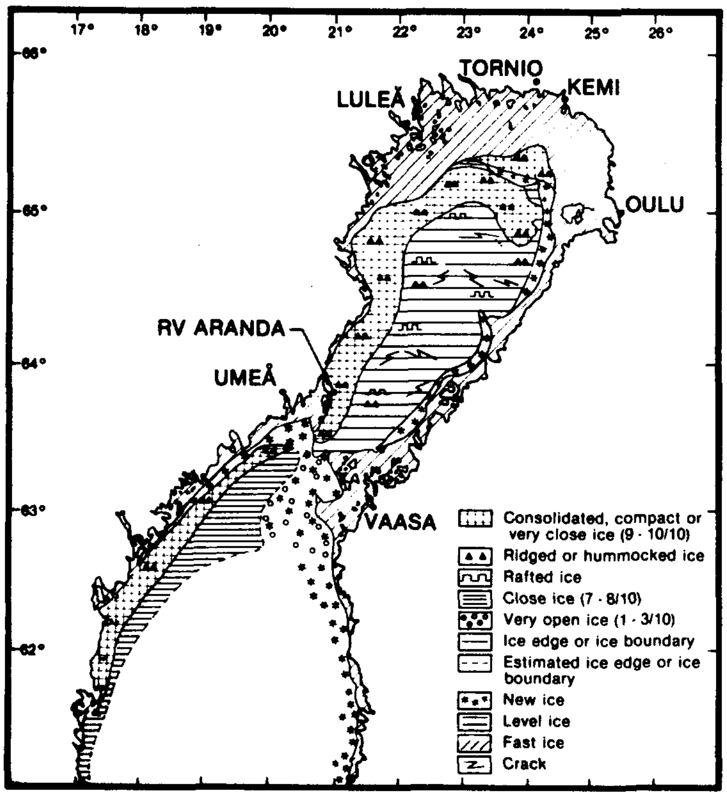


Figure 3. Sea ice conditions at the start of the BEPERS'88 project. (Map based on information from the Finnish Institute for Marine Research.)

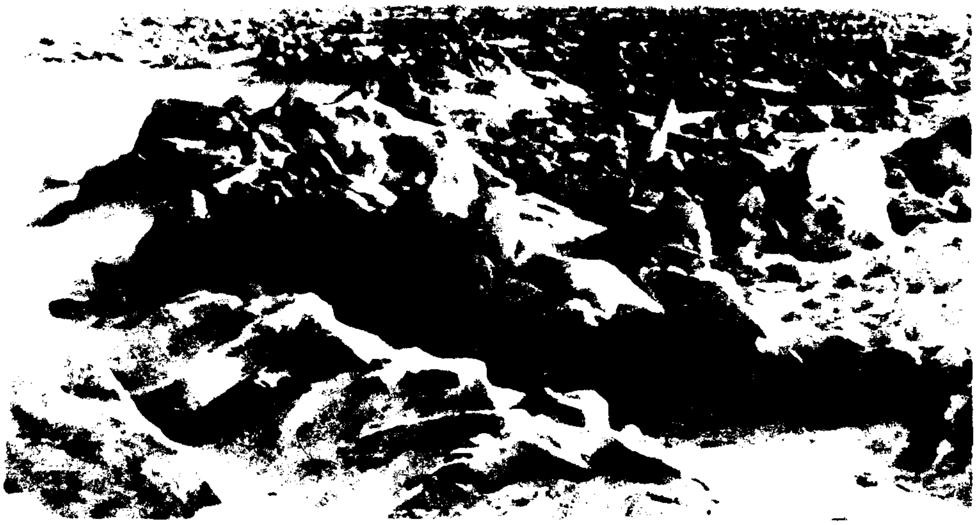


Figure 4. Highly deformed pressure ice in the immediate vicinity of the RV Aranda. *Individual ice blocks were 15–20 cm thick.*

The fast ice areas are usually in water with depths of less than 5–15 m. Farther offshore the pack ice is extremely dynamic, drifting in response to winds and currents and forming both complex lead systems and large pressure ridges. Ice floe drifts during storms can be as large as 20–30 km/day. The shipping that moves through the bay during the winter is significantly affected by ice pressure, ice movements and pressure ridges.

Ice conditions at the start of BEPERS'88 are indicated in Figure 3. These conditions were typical of a light ice year such as occurs, on average, once in 4–5 years. This resulted in the deployment of ships farther north in the bay than had been originally intended. The meteorological conditions, leading to a lighter ice year than usual, are also reflected in the low thicknesses and high temperatures of the ice encountered during the experiment.

The Finnish ship RV *Aranda*, which served as a base for our operations, was emplaced with the assistance of the Swedish icebreaker *Tor* in fast ice near the edge of the pack close to a small island located off the northeast corner of the island of Holmön east of Umeå, Sweden. Because extremely rough ice conditions made surface travel both difficult and dangerous (Fig. 4), most sampling was carried out near the ship. Limited amounts of helicopter time also allowed some sampling of the ice in the channel between Holmön Island and the mainland, as well as in the ice pack nearer the center of the bay. (Additional sea ice samples were also obtained by field parties on the *Tor*, which operated in the ice pack about 90 km to the north northeast of the *Aranda* [Fransson et al. 1989].) Immediately after completion of the BEPERS'88 field operations, additional fast ice samples were collected in the vicinity of Tornio, Finland, located at the northern end of the bay near the Finnish–Swedish border. Preliminary results of ice structure and salinity measurements obtained during BEPERS'88 are reported in Weeks et al. (1990a,b).

SAMPLING AND ANALYTICAL TECHNIQUES

Sampling was carried out by removing either cores or blocks from the ice sheets. Immediately upon retrieval of a sample, ice temperatures were taken at several depths by inserting a probe thermometer into holes drilled into the side of the sample. At the coring sites at least two cores were drilled, one being used for salinity and temperature measurements and the other being retained exclusively for crystal structure and stratigraphic studies. Cores used for salinity were cut on site into samples that were then placed in containers and returned to the *Aranda*. Salinities were then deter-

mined by measuring electrolytic conductivities of the melted samples. In converting conductivities to salinities it was assumed that the ratios of the major ions in brackish water were the same as those in standard sea water. This assumption is justified on the basis of published analyses of Baltic Sea and Bay of Bothnia waters by Grasshoff and Voipio (1981), confirmed subsequently by chemical analyses at CRREL of samples collected during the experiment.* The brine and gas volume and densities of the ice were calculated using relations from Cox and Weeks (1983), with the modifications of Leppäranta and Manninen (1988) included to deal with low salinities and nonmelting ice temperatures in the range between −2.0 and 0.0°C. On occasion ice densities were also determined from measurements of the mass and volume dimensions of cylindrical core samples.

Vertical thick sections were cut from the bulk samples and examined on a light table to determine the ice crystal types (textures) present. Vertical and horizontal thin sections were also prepared with a microtome to examine the microstructure of interesting locations in the samples. Finally the c-axis orientations of a number of crystals in selected sections were measured on a Rigsby stage. Further discussion of these procedures can be found in Weeks and Gow (1978, 1980) and Tucker et al. (1987). It was initially planned to carry out these measurements during the evenings while in the field. However, the near-melting temperatures encountered during the experiment made this impossible (preparing sea ice thin sections at ambient temperatures higher than −5°C is very difficult). Instead, selected samples were stored in a small freezer on the ship and the thin section studies were carried out in the VTT (Technical Research Center) coldrooms in Espoo, Finland. At the completion of this work, selected thin sections and ice blocks were stored in a freezer, awaiting shipment to CRREL for more detailed microscopic examination of brine layer spacings and crystal structure. Unfortunately the freezer failed and these samples were lost.

* Unpublished data, D. Meese, CRREL.

RESULTS AND DISCUSSION

For convenience of presentation of data, sites have been grouped as follows:

Group A: Four sites located in fast ice, three of which were situated in the immediate vicinity of the *Aranda* and the fourth located in the channel just west of Holmön Island;

Group B: Three sites located to the east and south of the *Aranda*;

Group C: Seven sites located in the so-called Intensive Study Area near the *Aranda*;

Group D: Three sites located at the north end of the Bay of Bothnia, near the town of Tornio.

Principal data sets obtained from all four groups are listed in Tables 1 and 2.

Group A

The locations of sites in this group (Sites 1–4) are shown in Figure 5. Water salinities at the four sites ranged from 3.7 to 3.9‰ corresponding to freezing temperatures of −0.18 to −0.21°C. Near-surface ice temperatures varied from −4.6°C at Site 1 to higher than −3.0°C at the remaining three locations. Snow depths generally varied from 5 to 15 cm, with the smaller depths corresponding to lower ice surface temperatures. Commonly the ice was within 2°C of its melting temperature. Ice temperature profiles were approximately linear. Salinity profiles yielded

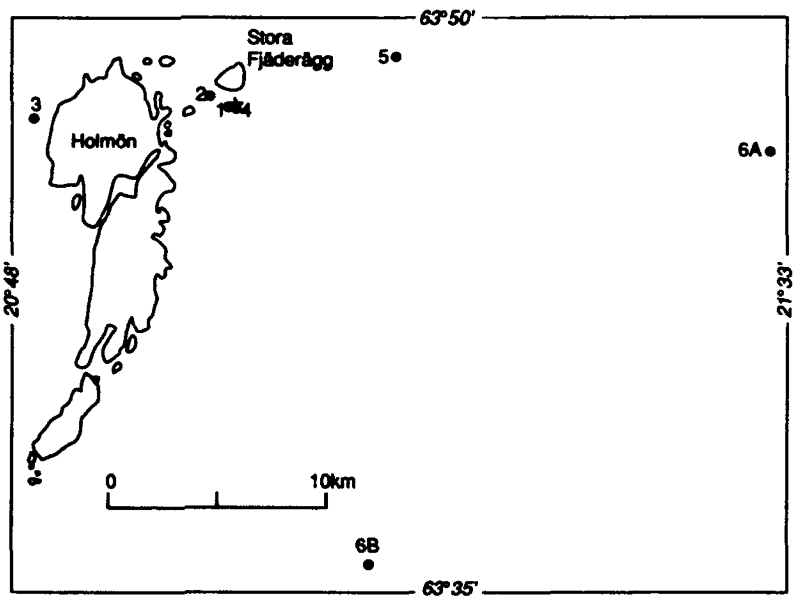


Figure 5. Locations of Group A and B sampling sites. The location of the RV Aranda *is marked with a cross near Site 4.*

Table 1. Ice properties, Bay of Bothnia, 1988.

Group	Date	Site no.	Lat./long.	Cores drilled	Ice thickness (cm)	Snow thickness (cm)	Bulk ice salinity (‰)	Water salinity (‰)
A Sites located in fast ice	3 Mar 88	1	63°47.8'N 21°00.8'E	6	40–45	5	0.79–1.07	3.8–3.9
	5 Mar 88	2	63°48.0'N 20°59.0'E	5	41–43	6–8	0.76–0.83	3.9
	7 Mar 88	3	63°47.5'N 21°49.3'E	2	46	8–10	0.78	3.7
	8 Mar 88	4	63°47.8'N 21°00.8'E	2 blocks	11	0–1	0.99	nd
B Sites located in drifting pack ice	8 Mar 88	5	63°49.2'N 21°10.2'E	3 blocks	36	0–15	0.58–0.81	3.7
	10 Mar 88	6A	63°46.5'N 21°31.7'E	2 blocks	29	1–5	0.66	3.6
	10 Mar 88	6B	63°35.5'N 21°08.4'E	2 blocks	36–37	1–4	0.59	4.1
C Sites in intensive study area located near *Aranda*	6 Mar 88	A1+800	63°47.0'N 21°00.3'E	2	50–52	12–20	0.68	3.8
	6 Mar 88	A1+600		2	56–64	10–14	0.66	nd
	6 Mar 88	A1+400		2	51	12–22	0.72	3.8
	6 Mar 88	A1+200		2	47–48	5–8	0.96	nd
	6 Mar 88	A1	63°47.5'N 20°59.9'E	2	46–48	8–12	1.03	nd
	9 Mar 88	A1–200		3	44–46	10	0.87	3.8
	9 Mar 88	A1–400		2	59	3	1.21	nd
D Sites located near Tornio	15 Mar 88	T1	65°44.7'N 24°13.5'E	1 block	69	38	0.06	0.035
	15 Mar 88	T2	65°39.3'N 24°14.0'E	1 block	57	38	0.12	0.038
	15 Mar 88	T3	65°40.3'N 24°13.7'E	1 block	76	25–52	0.77	0.043

peak values of just over 2‰, with generally lower salinities of less than 1‰ being observed with increasing depth in the ice. The attainment of near-constant salinities was generally associated with the onset and growth of congelation ice. The salinities of other ice types were significantly more variable. In addition to columnar congelation ice, two other ice types were identified:

- *Granular ice* of variable grain size formed either from the accumulation of surface slush and frazil crystals or from the freezing of water-soaked snow; and
- *Transition ice*, ice that appears to be an intermediate state resulting from oscillations in growth of granular and columnar textures; transition ice commonly displays very irregular horizontal banding, with the crystals in

Table 2. Ice crystal types in the Bay of Bothnia, 1988.

Site	Granular (%)	Transition (%)	Columnar (%)
1	11	80	9
2	12	28	60
3	24	43	33
4	0	9	91
5	14	42	44
6A	41	0	59
6B	42	0	58
A1+800	70	30	0
A1+600	58	22	20
A1+400	nd	nd	nd
A1+200	81	0	19
A1	83	0	17
A1–200	46	11	43
A1–400	42	20	38
T1	0	0	100
T2	0	0	100
T3	53	47	0

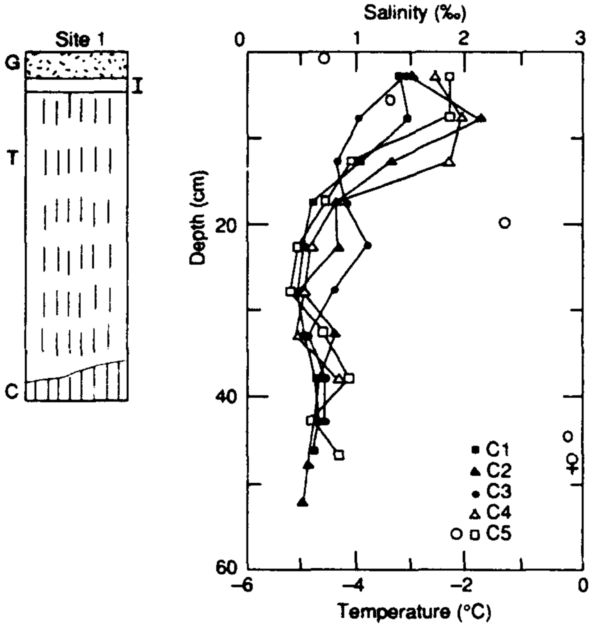


Figure 6. Vertical ice structure diagram, salinity profiles and ice sheet temperature data from Site 1. The symbols G, T and C in the structural profile denote granular, transition and columnar (congelation) ice, respectively. At this site the granular and transition ice crystal types were separated by a 1- to 2-cm-thick ice layer designated I. Temperature data are indicated by open circles; the cross directly beneath the near-bottom ice temperature value is the measured water temperature.

some bands exhibiting a definite elongation in the vertical (growth) direction, a feature that possibly indicates incipient development of a columnar (crystal) texture.

Horizontal c-axis orientations were common in congelation ice. In addition, in some of the thicker congelation ice, various degrees of c-axis alignments within the horizontal plane were also observed. It should be noted that, in the lower portions of a number of the cores of congelation ice, a platy substructure generally similar to that characteristically developed in normal sea ice was observed. This indicates that a nonplanar dendritic-type interface also forms during quiet freezing of brackish water with salinities of around 4‰, a salinity that is roughly an order of magnitude less than the salinity of arctic sea water. This observation is in agreement with the experimental results of Weeks and Lofgren (1967), who observed the change from a planar to a nonplanar interface to occur at concentrations of roughly 1‰ during the freezing of salt solutions.

Site 1

This site was located in fast ice about 100 m west of the *Aranda*. Six cores were collected, all within a 1-m^2 area. Five cores were used primarily for salinity and temperature measurements and the sixth was used for detailed studies of ice crystal structure, including an analysis of the c-axis fabric. The ice sheet within this relatively narrow sample spacing ranged in thickness from 40 to 54 cm and was overlain by 5 cm of snow. The salinity of the underlying water varied from 3.8 to 3.9‰.

A diagram of the vertical ice structure, together with the five salinity profiles and the temperature data, is presented in Figure 6. Structurally the ice at this location consisted predominantly of transition ice (80%), which was underlain by congelation ice (9%) and overlain by a 2-cm-thick ice layer and granular ice that collectively represented 11% of the total ice sheet thickness. The granular ice zone included some snow ice as well as frazil ice.

The texture of the transition ice layer and the inclined nature of its junction with the congelation ice are interpreted as indications of disturbed ice growth, resulting either from turbulence in the water column or from disturbances associated with the formation of pressured ice in the immediate vicinity of Site 1. The varied textures contributing to the structure of the ice at Site 1 are shown in a series of thin section photographs in Figure 7. Included are the full 40-cm-long vertical structure section for Core 6 together with four horizontal thin sections from representative levels in the ice. The single fabric measurement at 38 cm displays a significant c-axis alignment in the horizontal plane. Present thinking, based on field studies and laboratory experiments, attributes such an alignment to the directional control of currents at the ice/water interface, with the favored alignment direction of the c-axes paralleling that of the current (Gow and Weeks 1977, Weeks and Gow 1978, 1980, Langhorne 1983, Stander and Michel 1989). Currents at the ice/water interface at this location were not measured. However, the northwest–southeast orientation of the c-axis alignment in azimuthally oriented cores would indicate that this alignment developed in response to either a northwest or southeast current (or possibly both) at the ice/water interface.

Dirt particles were observed in transition ice of Core 6 and in one other core. Though the precise origin of this material is not known, it likely originated as particles suspended in the water column, which subsequently became incorporated in the transition ice during freezing.

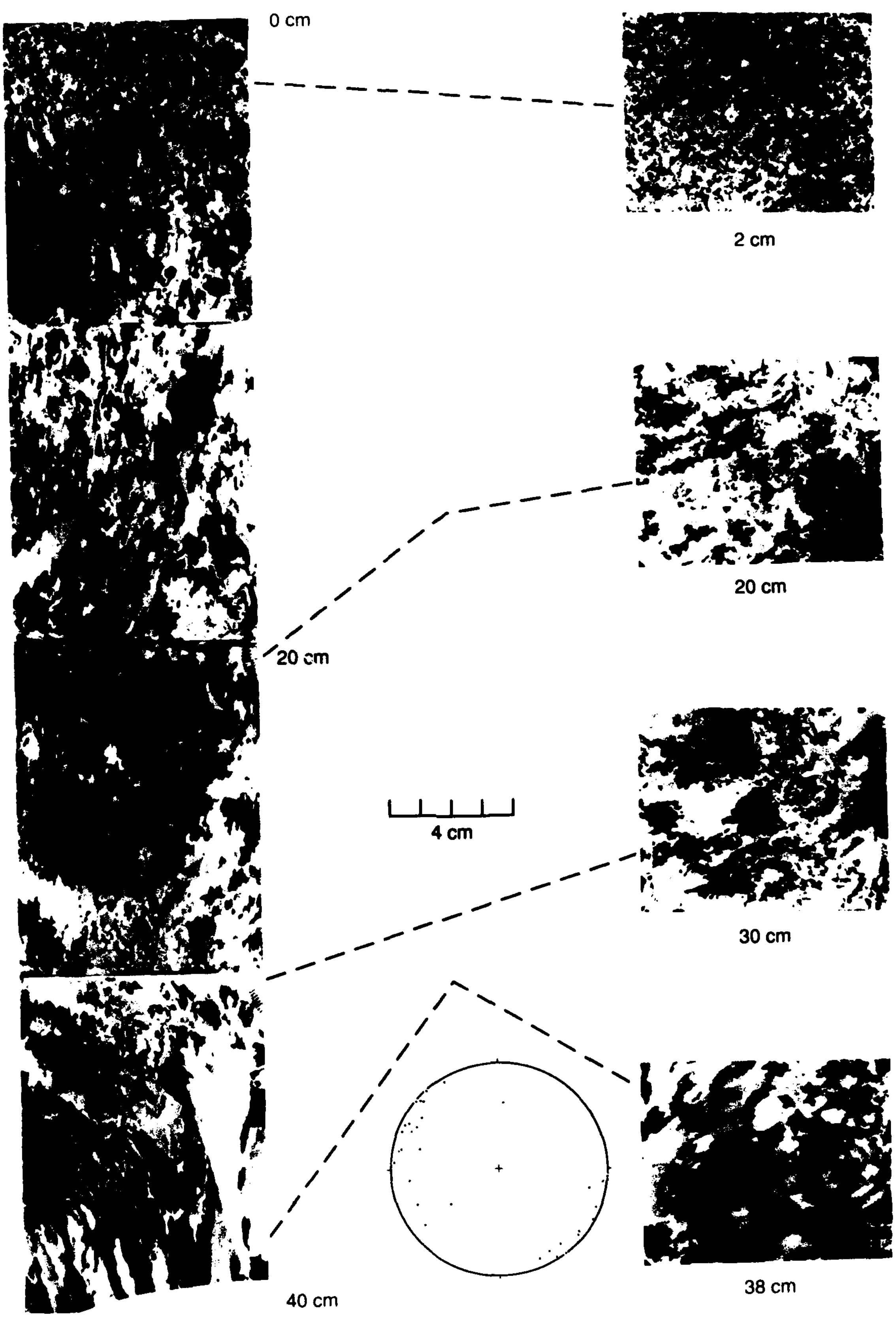


Figure 7. Full vertical section and four representative horizontal thin-section photographs of the crystal structure of ice at Site 1. All sections are photographed between crossed polarizers. A c-axis fabric diagram of ice from 38 cm is also shown.

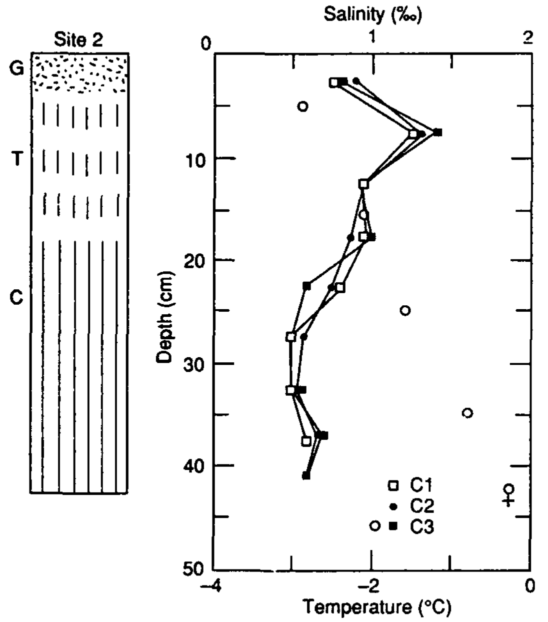


Figure 8. Vertical ice structure diagram, salinity profiles and temperature data from Site 2 located near Stora Fjäderägg, Sweden. The symbols are the same as in Figure 6.

Salinity profiles showed substantial lateral variability that did not diminish until a depth of 35–40 cm. This variability occurs mainly in the transition ice, with the highest salinities occurring in the top 20 cm coincident with earlier stages of ice growth when turbulence in the water column (e.g. wave action due to wind) was likely at its maximum. The attainment of near-constant salinities below 35–40 cm probably coincided with the onset of growth of congelation ice under fairly uniform freezing conditions.

Site 2

This site was located in undeformed ice at the southwest end of Stora Fjäderägg. Five cores were drilled within an area of 1 m^2. Cores 1–3 were used for salinity determinations, with Core 3 also being used for measuring ice temperatures. Core 4 was reserved for thin-section studies, with additional sections being prepared from Core 5. The ice thickness varied from 41 to 43 cm, indicative of uniform and relatively undisturbed growth. The ice sheet was overlain by 6–8 cm of snow and underlain by brackish water with a salinity of 3.9‰. A diagrammatic structure section, together with three salinity profiles and temperature data from Core 2, are presented in Figure 8. Structurally the ice at Site 2 was composed of 5 cm of granular ice underlain by transition ice, extending to a depth of 17 cm. This in turn was underlain by congelation ice to a depth of 43 m. Congelation ice at this location thus represents 60% of the total ice sheet thickness. The platelet structure that is characteristic of dendritic ice growth was clearly visible in the bottom sections of all five cores.

The three salinity profiles are very similar, with the highest salinities (1.3–1.4‰) occurring in the transition ice. Again, near-constant salinities of 0.6–0.8‰ were observed in the congelation ice.

The textural characteristics of the ice (Fig. 9), together with the relatively rapid development of a preferred c-axis fabric in the congelation ice, point to growth of most of the ice sheet under conditions of relatively quiet freezing. At a core depth of 30 cm, 12 cm after the onset of congelation growth, the c-axes of the crystals had become oriented within the horizontal plane, and by 40 cm a significant directional alignment of axes within the horizontal plane was present. The direction of this alignment was parallel to the channel presumed to exist between Stora Fjäderägg and a smaller island to the southwest. In fact the positioning of Site 2 was largely based on this assumption. While current measurements are not available to demonstrate a parallelism between the mean current direction and the mean c-axis alignment, the similarity between the c-axis alignment direction at 40 cm and the presumed direction of the current through the channel supports the view of current-controlled c-axis alignment at this location.

Though Sites 1 and 2 were only about a kilometer apart, the salinity profiles and composition of the ice at the two sites are radically different, illustrating the degree to which ice properties in the Bay of Bothnia can change over relatively short distances in what appears to be the same piece of fast ice.

A nearly linear temperature profile was measured at Site 2; a temperature of −0.3°C measured in the water directly under the ice is within 0.1°C of the calculated freezing temperature of brackish water of 3.0‰ salinity.

Site 3

Site 3 was located in fast ice about 1 km west of the lighthouse situated on the northwest shore of Holmön Island, Sweden. This site was chosen because the ice in this area gave a very low radar return on SAR imagery. The ice surface at Site 3

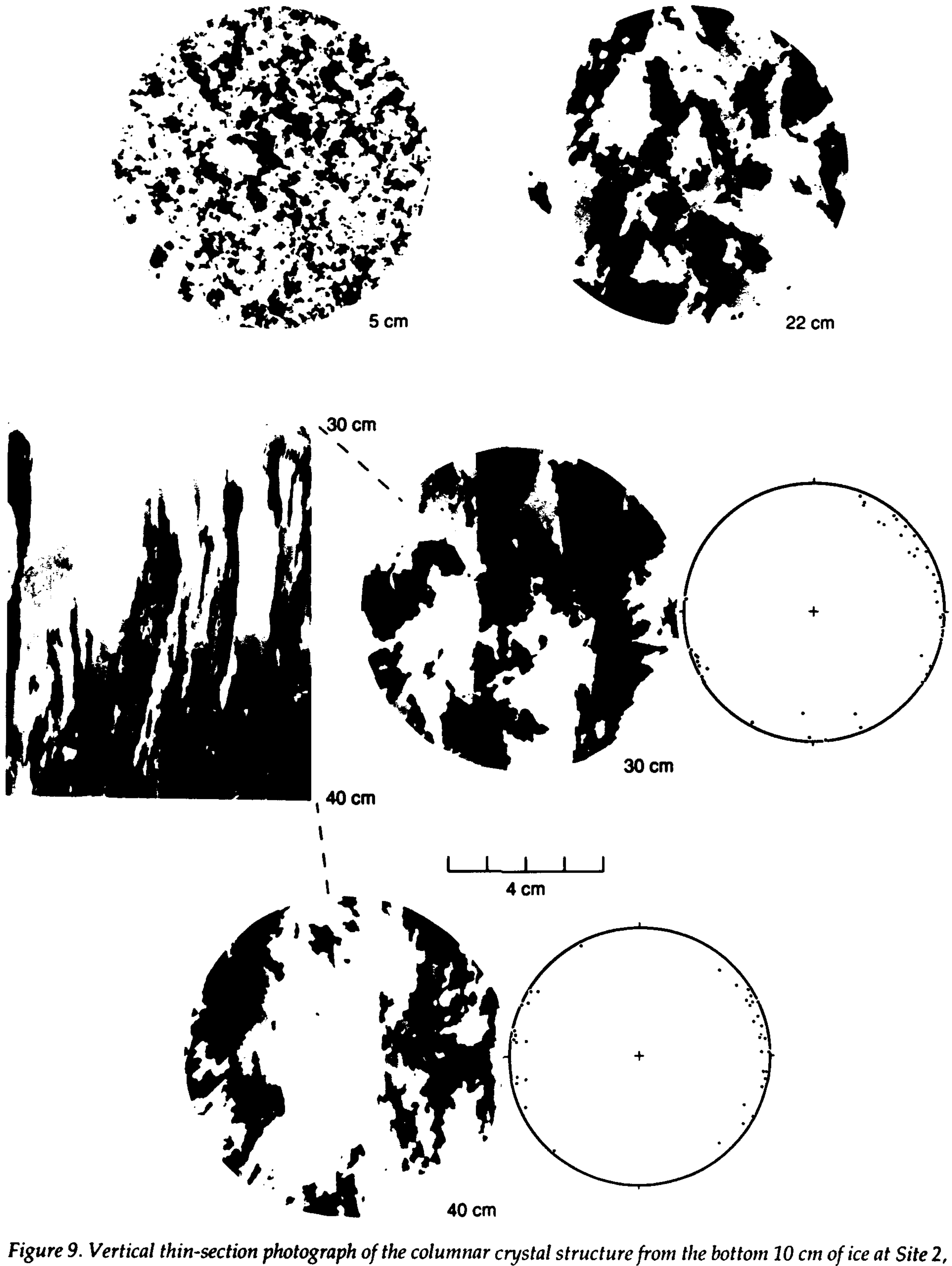


Figure 9. Vertical thin-section photograph of the columnar crystal structure from the bottom 10 cm of ice at Site 2, together with four representative horizontal thin-section photographs and two c-axis fabric diagrams.

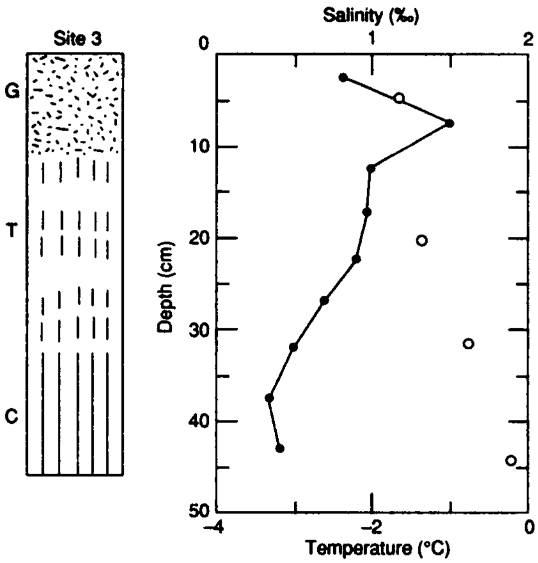


Figure 10. Vertical ice structure diagram, salinity profile and temperature data for ice at Site 3 located near Holmön Island, Sweden. The symbols are the same as in Figure 6.

proved to be very flat and completely devoid of rubble or upturned ice blocks. A snow cover measuring 8–10 cm deep overlaid an ice sheet 46 cm thick. Two cores were drilled for salinity, temperature and structural studies (Fig. 10).

At this site 11 cm of granular ice was underlain by 20 cm of transition ice followed by 15 cm of congelation ice. The salinity profile closely resembled the profiles from the Site 2 cores. However, the Site 3 core yielded higher salinities in the granular ice component, whereas the transition ice was the saltiest at Site 2. Again the lowest salinities were obtained from the congelation ice. The salinity of the underlying water was 3.7‰. The temperature profile was nearly linear, with temperatures ranging from –1.7°C at a depth of 5 cm to –0.2°C 2 cm from the bottom. Textural studies (Fig. 11) showed relatively fine-grained transition ice underlain by moderately coarse-grained columnar congelation ice with horizontal c-axes. Only a very weak alignment of c-axes was discernible in the bottom ice, suggesting that, unlike the situation at Site 2, the congelation ice at Site 3 had formed in the absence of a significant directional current.

Site 4

This site was located in thin undeformed ice that had formed in the ship track directly astern of the *Aranda*. Open water behind the ship began freezing during the afternoon of 2 March 1988, and by 3 March a sheet of ice 11 cm thick, substantially free of snow, had developed. Two blocks of ice were cut from the ice sheet. Profiles of structure and salinity, together with ice temperature measurements, are presented in Figure 12. A maximum salinity of 1.25‰, measured in the top 1–2 cm of ice, coincided with the onset of congelation ice growth. The salinity then decreased to 0.68‰ between 2 and 9 cm before increasing to 1.15‰ in the lowest 2 cm of ice. The temperature in the ice sheet increased linearly from –1.5°C in the top centimeter to –0.2°C at the bottom.

Structurally the ice consisted of 91% congelation ice. The lack of granular (frazil) ice at the top of the sheet suggests that freezing occurred under quiescent conditions. The top centimeter of ice consisted largely of platy crystals with vertical c-axes, with occasional dendritic crystals interspersed between them. This texture is typical of spontaneous freezing in the absence of nucleating particles. However, by 2 cm the platy crystals had been largely replaced by columnar crystals, resulting in a fabric consisting of randomly oriented c-axes. Continued growth of the columnar ice was also accompanied by a progressive increase in the cross-sectional areas of the crystals, as the horizontal thin-section photographs in Figure 13a demonstrate. Although the overall fabric was one in which the c-axes had become oriented within the horizontal plane, no significant alignment of c-axes had occurred. Also clearly shown in the thin-section photograph for 11 cm, and the enlargement of part of it (Fig. 13b), is the same ice plate–brine layer substructure of crystals that characterizes arctic sea ice grown from more saline water. This substructure results from the formation of a dendritic growth interface induced by the requirements of constitutional supercooling, a process by which brine is systematically incorporated *between* the plates (dendrites) of pure ice. The spacing of the brine layers in the bottom ice at Site 4 is about 0.7 mm, a value very similar to that observed in arctic sea ice at a similar stage of growth. However, the amount of salt entrapped in the brine layers of the Bay of Bothnia ice is much smaller than that trapped in arctic sea ice. In terms of bulk salinity this amounts to less than 1‰ salt entrapped in Bay of Bothnia ice at Site 4, for example, compared to about 8‰ measured in thin first-year ice in the Arctic. Interestingly enough these salinity entrapment values in Bay of Bothnia and Arctic sea ice are in roughly the same propor-

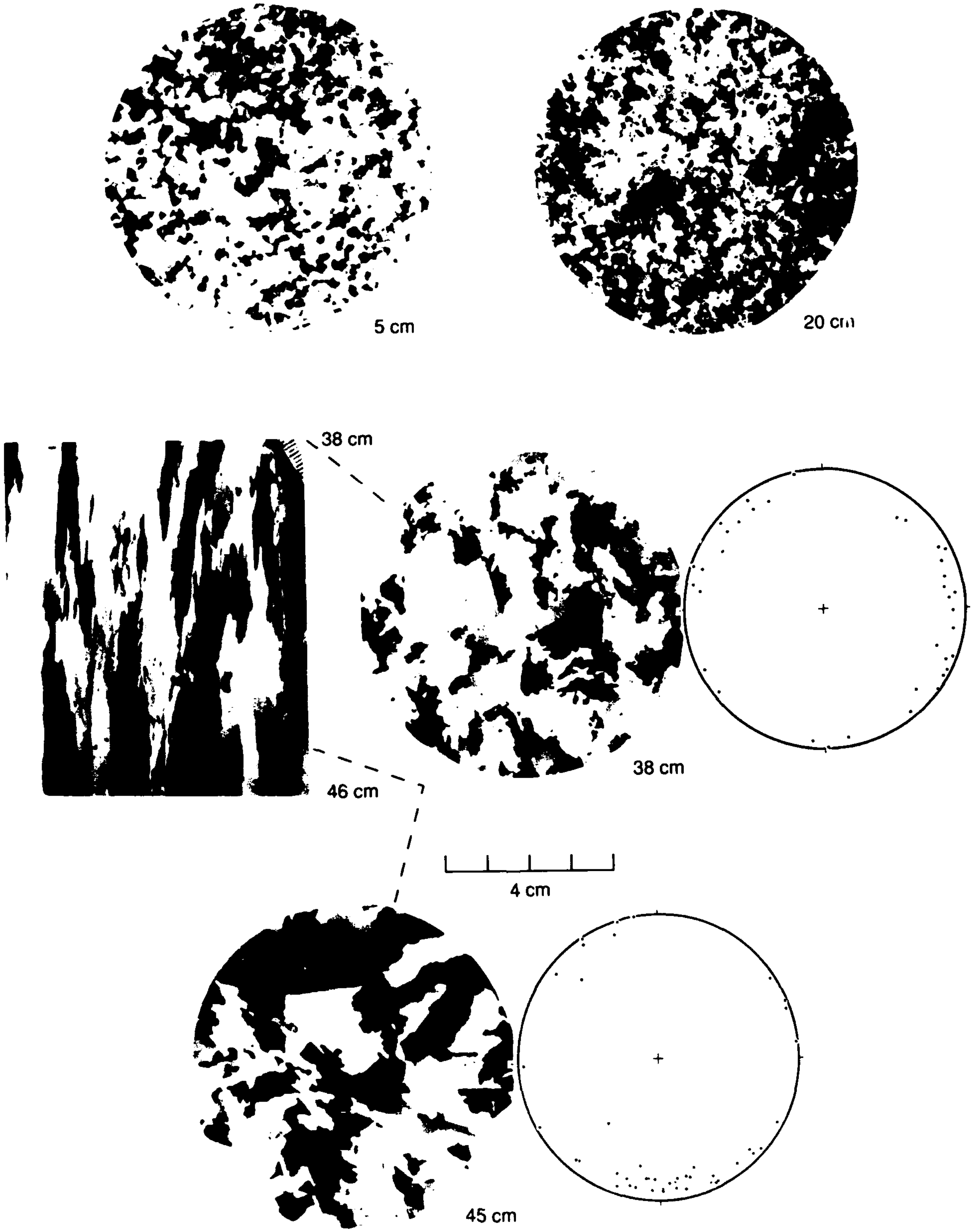


Figure 11. Vertical thin-section photograph of the bottom 8 cm of columnar ice at Site 3, together with four horizontal thin-section photographs and two c-axis fabric diagrams.

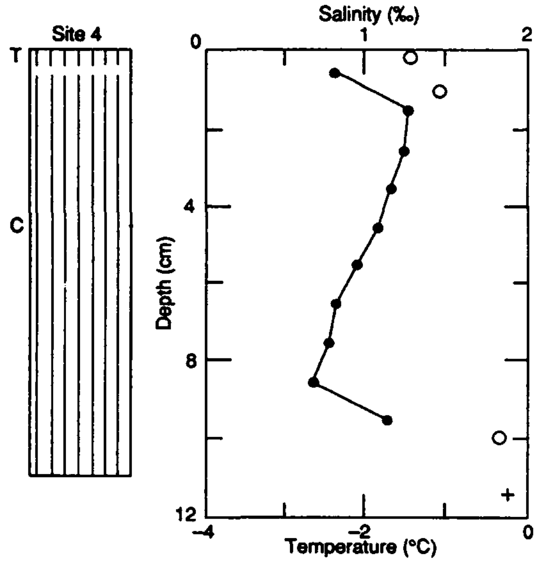


Figure 12. Vertical ice structure diagram, salinity profile and temperature data from Site 4 located in the refrozen ship track directly behind the RV Aranda. *The symbols are the same as in Figure 6.*

tions (1:8) as the salinities of the parent waters (4‰ in the Bay of Bothnia, 34‰ in the Arctic Ocean). Similar variations were observed in fast ice at Sites 1, 2 and 3. In short, it appears that the ratio of salt retained by the ice to that present in the parent waters holds over a very substantial range of salinities. In terms of salt rejection, about 80% of the salt is returned to the sea during freezing in both the Bay of Bothnia and the Arctic Ocean. This observation could bear critically on circumstances determining the salinity at which the change-over from a dendritic to planar interface occurs. The planar interface is typical of freshwater ice sheets, forming, for example, in lakes with dissolved ion concentrations possibly as high as 1000 μmho/cm, equivalent to a salinity of about 0.5‰. No definitive measurements of the exact conditions under which this change-over in interface morphology occurs are available, though limited investigation of the problem based on the freezing of NaCl solutions indicates that the transition occurs around a salinity of approximately 1‰ (Weeks and Lofgren 1967).

Group B

These sites include three locations on the drifting ice pack to the south and east of *Aranda* designated 5, 6A and 6B. The locations of the sites are shown in Figure 5. These sites were free of ridging although there was deformed ice in the general area. The salinities of the water directly beneath the ice varied from 3.6 to 4.1‰. The temperatures in the ice were −2.2°C or higher. Salinity profiles were similar to those at the Group A (fast ice) sites, with salinities exceeding 1‰ in the upper levels followed by salinities that decreased progressively with increasing depth. Structurally the ice at Site 5 was similar to that observed at the fast ice sites. However, at Sites 6A and 6B the congelation ice component was directly overlain by granular ice without any intervening transition ice.

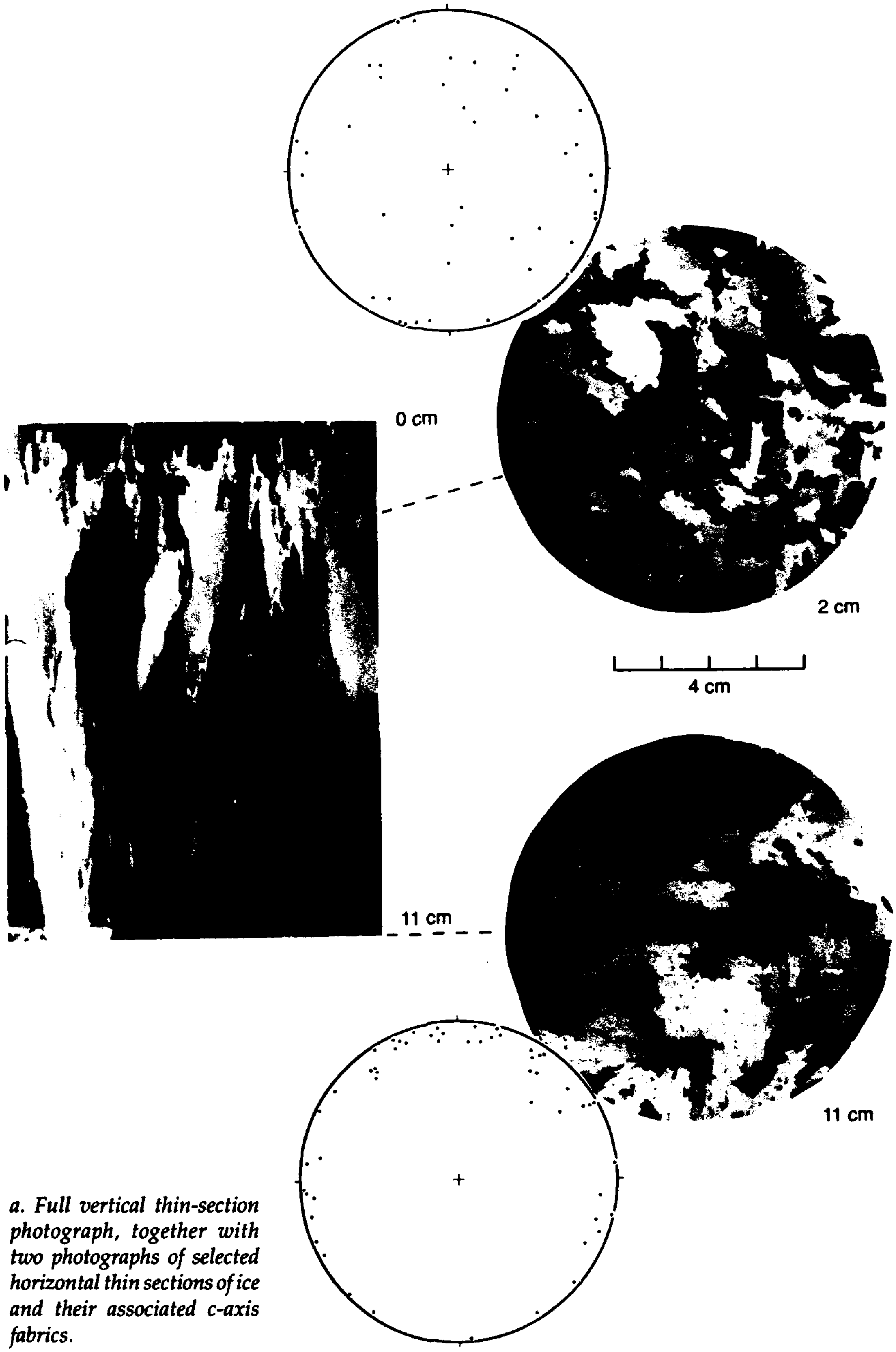
Site 5

This site was located on a large ice floe 6 km east of Stora Fjäderägg. Samples were collected in the form of ice blocks, all three being positioned within 5 m of each other. The surface of the floe was very flat with a thin snow cover 0–2 cm thick. The ice thickness at all three sites was 36 cm, and the salinity of the underlying brackish water was 3.7‰. The ice structure and salinity profiles are presented in Figure 14.

Structurally the ice at Site 5 consisted of 5 cm of granular ice underlain by 15 cm of transition ice and 16 cm of congelation ice. Changes in ice crystal type were clearly reflected in the salinity profiles, with the largest lateral variations in salinity occurring in the transition ice. This situation closely mimics that observed at Site 1, probably reflecting the disturbed hydrodynamic conditions under which the transition ice presumably formed.

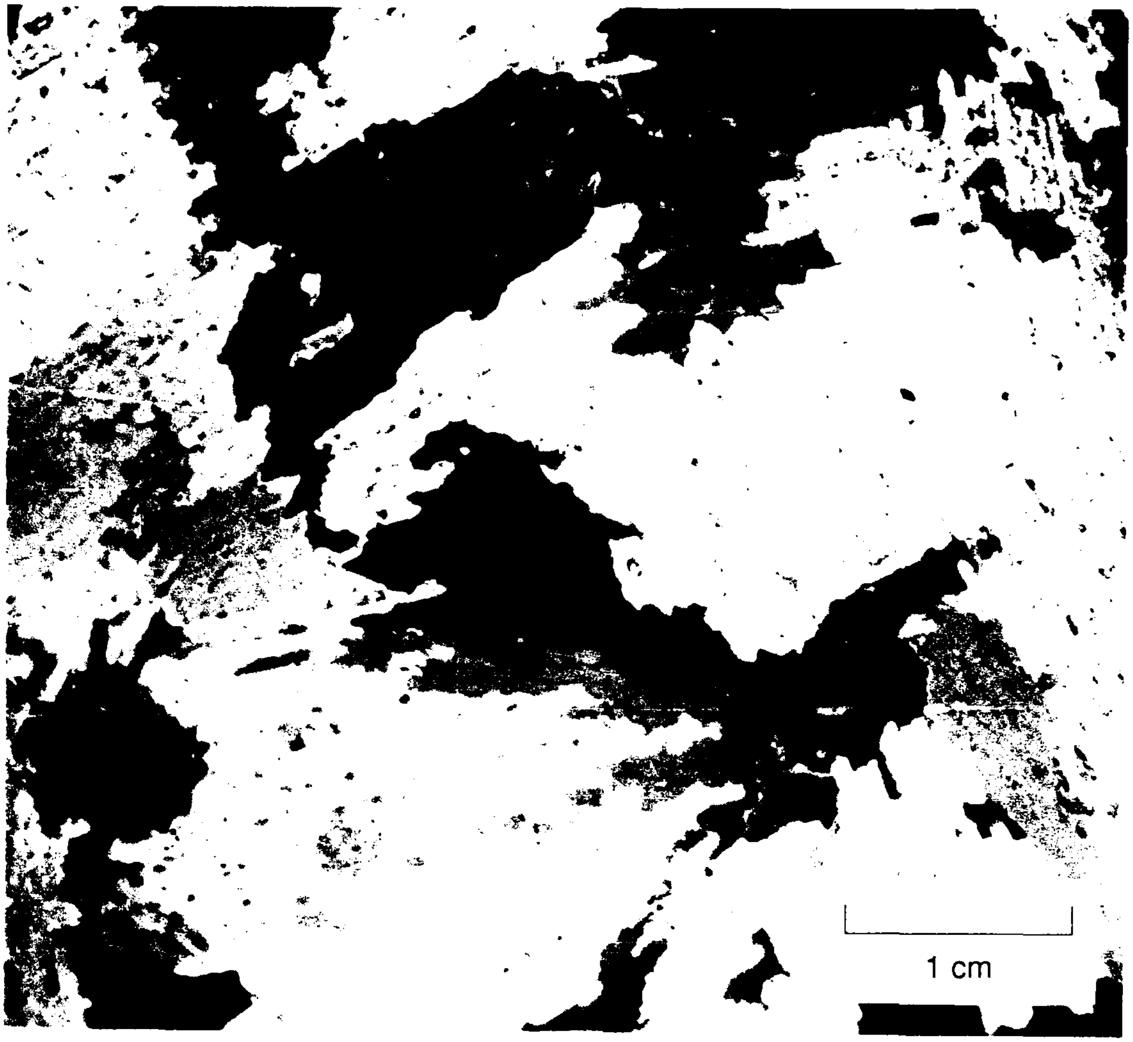
It is worth noting that ice with textures very similar to those of the transition ice in the Bay of Bothnia has also been observed in the Weddell Sea, Antarctica, by Eicken and Lange (1989), who linked its formation to ice deformation and a rough under-ice hydrodynamic regime. The same explanation may apply to earlier observations in the Bay of Bothnia by Omstedt (1985) and Fransson et al. (1989), who found granular and transition ice to occur frequently within the pack ice.

A full vertical thin section, together with four horizontal thin sections (Fig. 15), clearly shows the contrasts in crystalline texture and the relatively sharp transitions between the three ice types at Site 5. In particular the texture of the congelation ice at this site more closely approximated that observed in arctic sea ice than was observed at any other site we visited during BEPERS'88. The fabric diagram at 36 cm shows a well-developed c-axis orientation within the horizontal plane; however, there was no significant c-axis alignment within this plane.



a. Full vertical thin-section photograph, together with two photographs of selected horizontal thin sections of ice and their associated c-axis fabrics.

Figure 13. Thin-section photographs of the columnar ice structure at Site 4.



b. Enlarged photograph of the thin section from 11 cm, showing ice plate and brine layer substructure of the crystals.

Figure 13 (cont'd). Thin-section photographs of the columnar ice structure at Site 4.

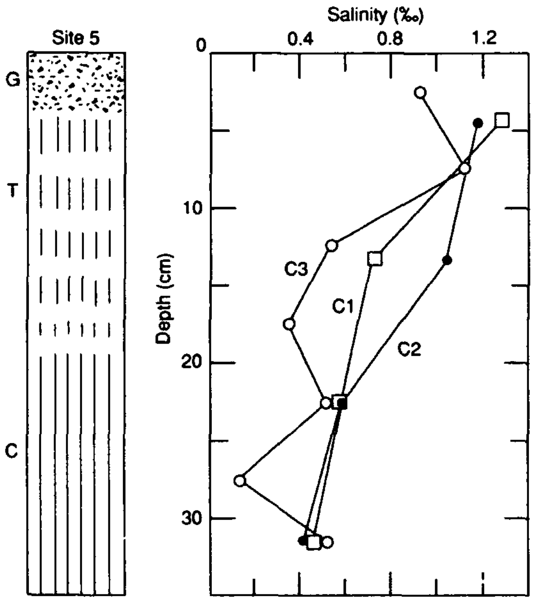


Figure 14. Vertical ice structure diagram and salinity profiles from Site 5 located on drifting pack ice due east of Stora Fjäderägg. The symbols are the same as in Figure 6.

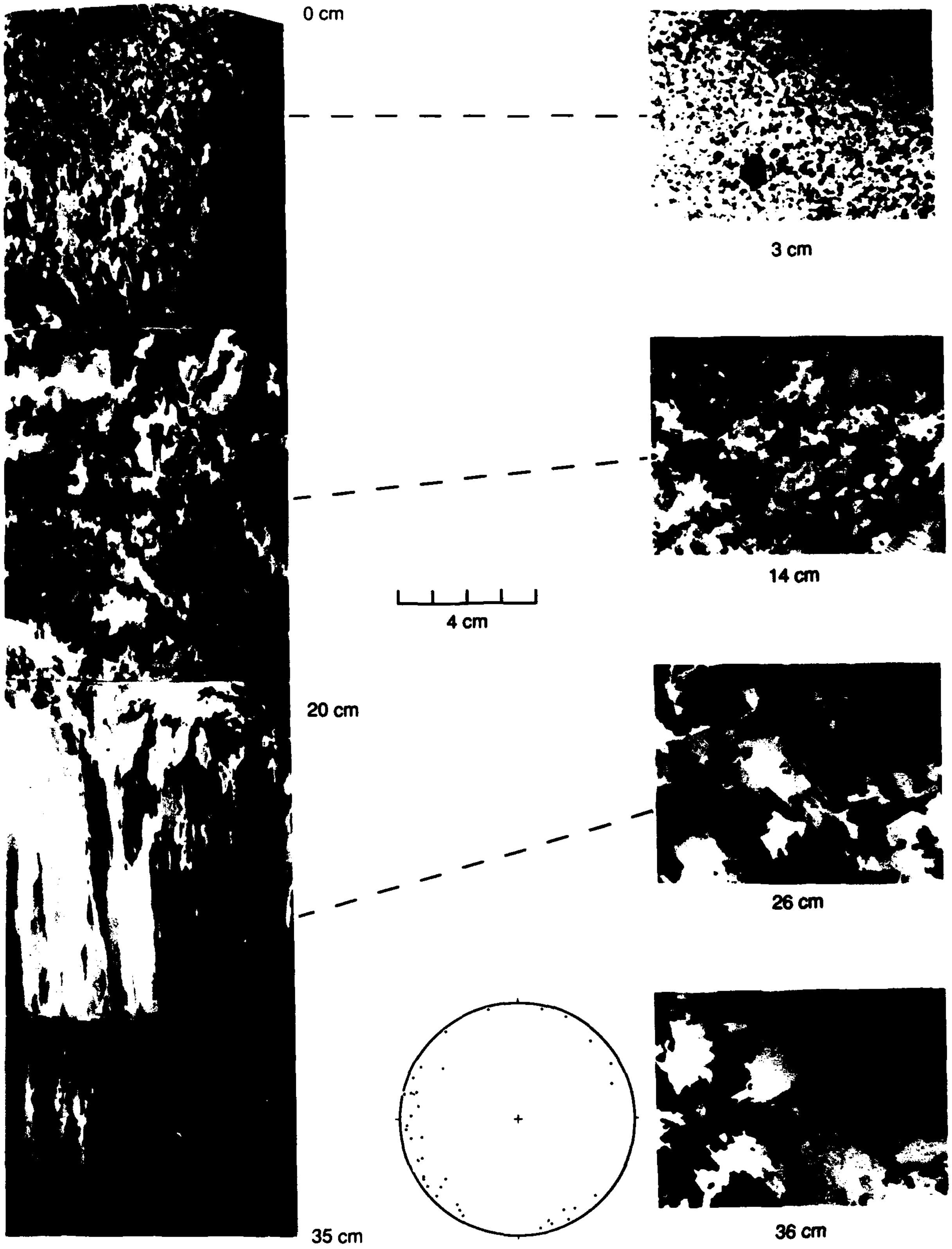


Figure 15. Full vertical thin-section photograph of the crystal structure of ice at Site 5, together with four representative horizontal thin-section photographs and a c-axis fabric diagram of the bottom ice at 36 cm.

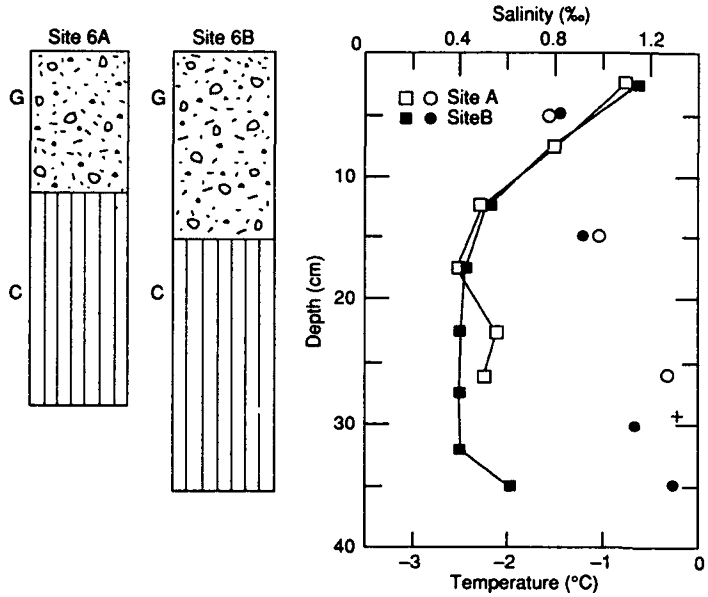


Figure 16. Vertical ice structure diagram, salinity profiles and temperature data for drifting pack ice at Sites 6A and 6B. The symbols are the same as in Figure 6.

Sites 6A and 6B

Though these two sites were located on separate floes more than 20 km apart, their structure and salinity characteristics were so similar as to merit joint discussion of their ice properties. Site 6A was located approximately 24 km east of the *Aranda;* Site 6B was approximately 21 km south of the *Aranda*. Both floes were very flat and covered with snow that varied in thickness from 1 to 5 cm. However, ice thicknesses differed appreciably at the two sites: 29 cm at Site 6A, increasing to 37 cm at site 6B. At both sites two blocks of ice were extracted about a meter apart and were used for salinity and structural studies. As shown in Figure 16, ice from these two floes consisted of bubbly granular ice overlying congelation ice. No transition ice was identified at either site. Highly variable textures characterized the granular ice component, as demonstrated in the two horizontal thin sections from Site 6A (Fig. 17). Included were vein-like bodies of ice, which may have resulted from the freezing of water percolating from the surface downwards through a permeable snow layer. Congelation ice, representing nearly 60% of the total ice thickness at both sites, consisted of columnar crystals, which in the bottom parts of both floes show c-axis alignments that were the strongest we observed during the BEPERS experiment.

Salinity profiles from the two sites are very similar (Fig. 16), with the highest salinities in the upper part of the granular ice, decreasing progressively through the granular ice before attaining nearly constant values in the entire congelation ice component. The salinities of the underlying brackish water increased from 3.6‰ at Site 6A to 4.1‰ at Site 6B located nearly 25 km away.

Group C

These sites were all located in the so-called Intensive Study Area (ISA), which comprised a 1- × 2-km rectangle located south of the *Aranda* that included both fast and ridged ice. A photo of the ship's radarscope is reproduced in Figure 18 to show the rectangular layout of the ISA relative to the *Aranda* as well as the major topographic features of the ice in and beyond the ISA. Although most of the ISA was located in very ridged and rubbled ice, our sites were all located on relatively level ice in the western corner of the area. Figure 19 shows the positions of our sampling sites in some detail. For ease of identification our ice-coring sites were all located at flags marking the perimeter of the ISA. The primary purpose of this part of the experiment was to conduct ground truth studies of ice characteristics in conjunction with airborne SAR measurements. The ISA was very carefully laid out. As shown in Figure 19, this layout included a variety of radar reflectors, as well as black tarpaulins to facilitate easy identification from the air. The validation program ran from 6 to 9 March and included (in addition to the SAR observations) airborne measurements with a laser profilometer, an impulse radar, a radiometer and a radar scatterometer. Index measurements of physical properties measured in ice from this area and the percentages of ice types are listed in Table 1 and Table 2, respectively.

Sites A1 to A1+800

Along this line, oriented approximately in a northwest–southeast direction, cores were drilled at five sites, including A1. The line was characterized by a highly variable snow cover with thicknesses ranging, for example, from 5–8 cm at Site A1+200 to 12–20 cm at Site A1+800. The results of the structural and salinity studies are shown in Figure 20, which also includes temperature data from Site A1+800. Salinity measurements only were made at Site A1+400. Structurally the ice at the remaining four sites was dominated by granular

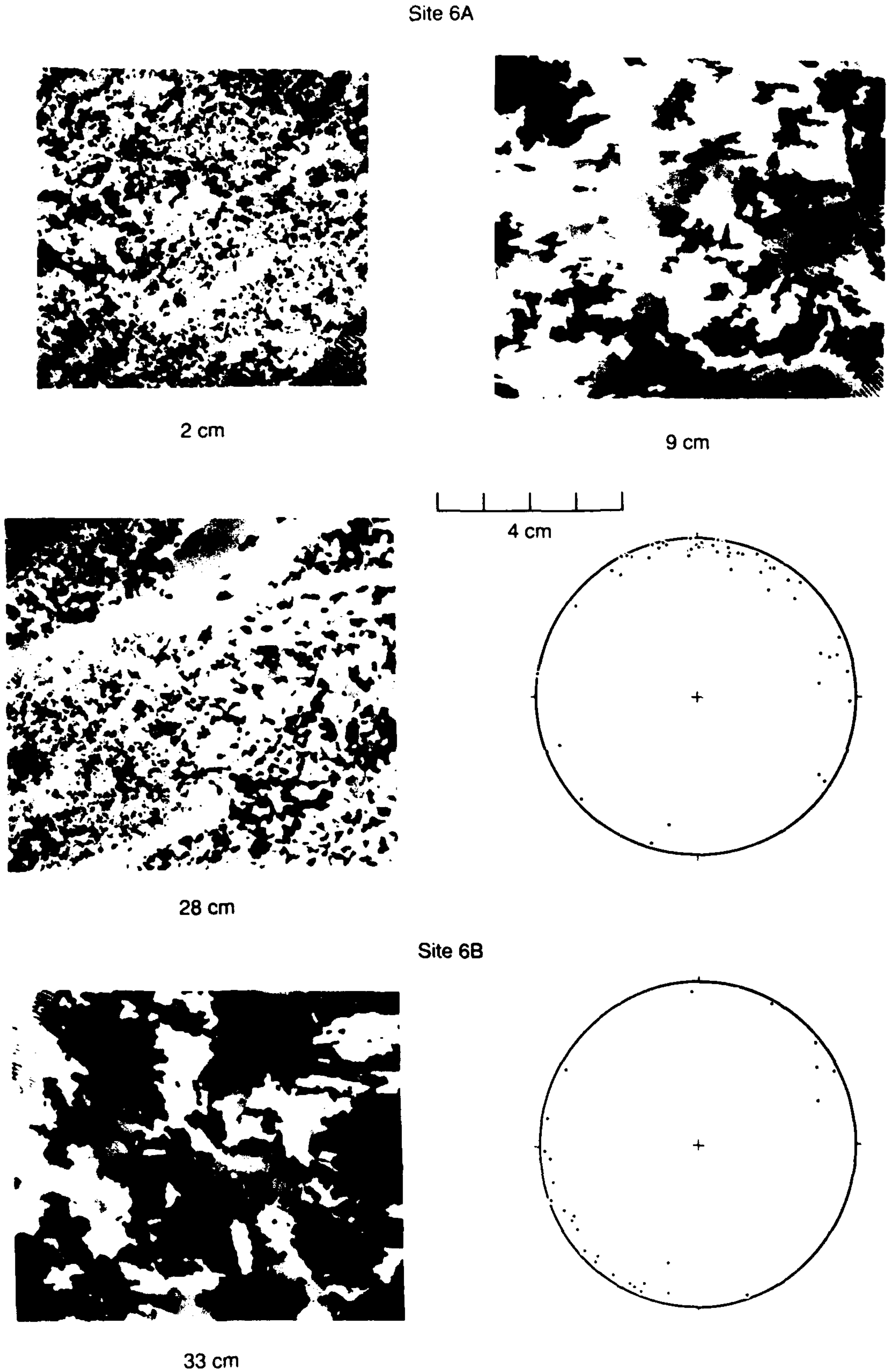


Figure 17. Horizontal thin-section photographs and c-axis fabrics of bottom ice from Sites 6A and 6B.

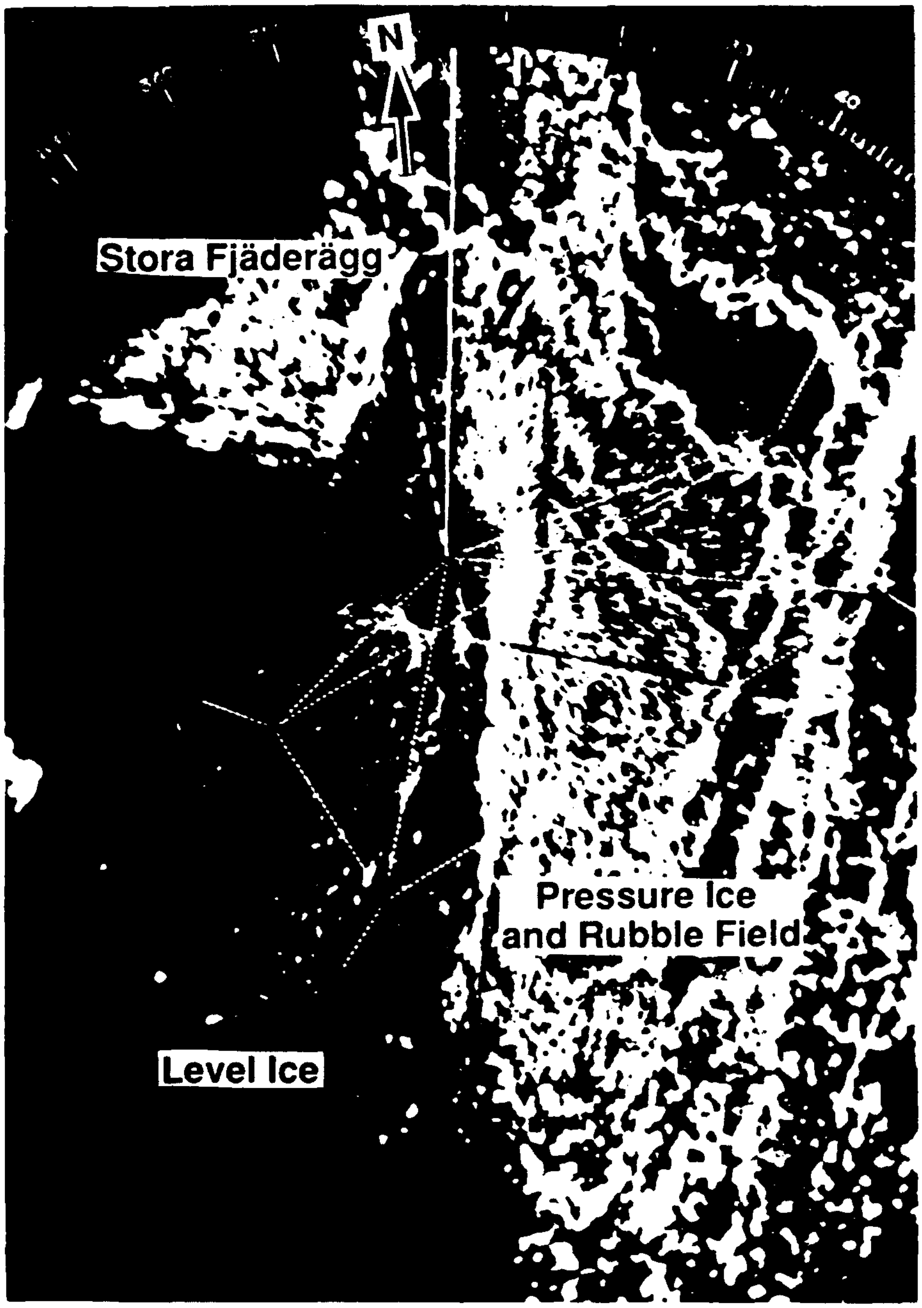


Figure 18. Portion of RV Aranda's *radar scope showing major topographic features and the layout of the Intensive Study Area superimposed.The RV* Aranda *is located at the intersection of the dashed and full lines.*

ice of highly variable texture and porosity; it comprised 83% of the ice sheet at Site A1 and 80% of the total ice thickness at Site A1+200. At both these sites the congelation ice was overlain directly by granular ice, with no identifiable intervening transition ice. At Site A1+800 the granular ice was underlain by transition ice with no trace of congelation ice. At Site A1+600 a layer of debris at a depth of 30–32 cm formed a distinct junction between the granular and transition ice. Dispersed brown particles were also observed in cores from near the bottom of the ice sheet at Site A1+800.

Thin-section structure photographs and some bottom section c-axis fabric plots are presented in Figure 21. The structure sections clearly show the variable nature of granular ice textures in this

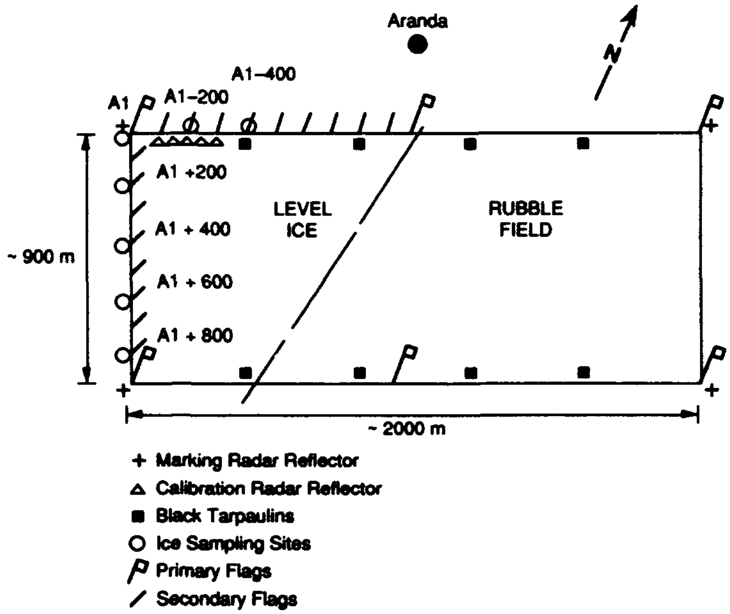


Figure 19. Details of the layout of the BEPERS'88 Intensive Study Area.

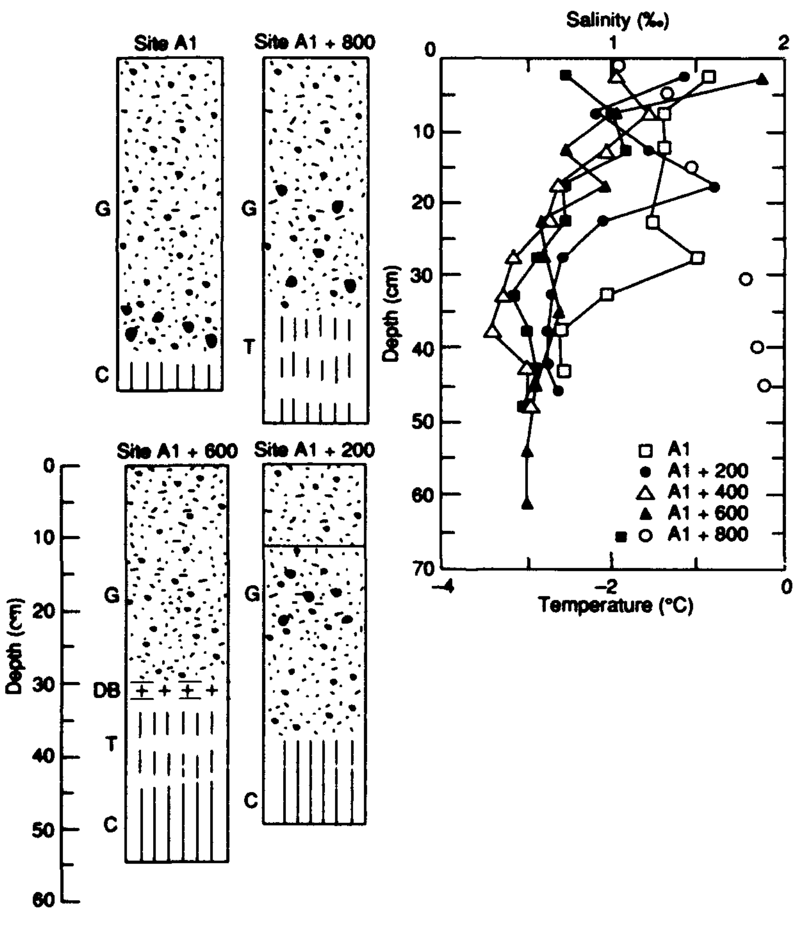


Figure 20. Vertical ice structure diagrams, salinity profiles and temperature data for Sites A1 through A1+800 in the Intensive Study Area. The symbol DB at Site A1+600 denotes a band of debris at a depth of 30–32 cm. The symbols are the same as in Figure 6.

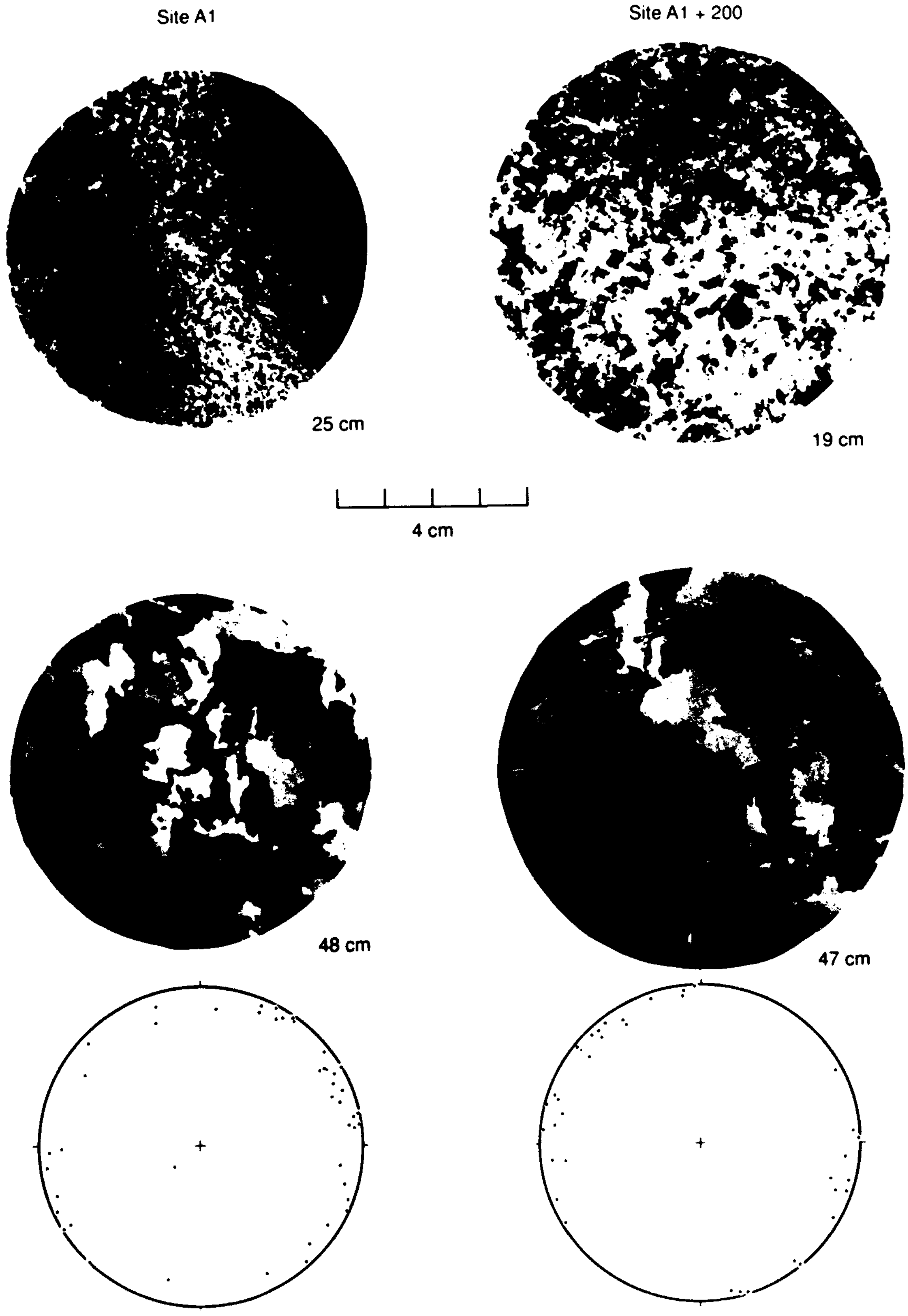


Figure 21. Thin-section photographs of the ice structure and c-axis fabrics of bottom ice at Sites A1, A1+200, A1+600 and A1+800.

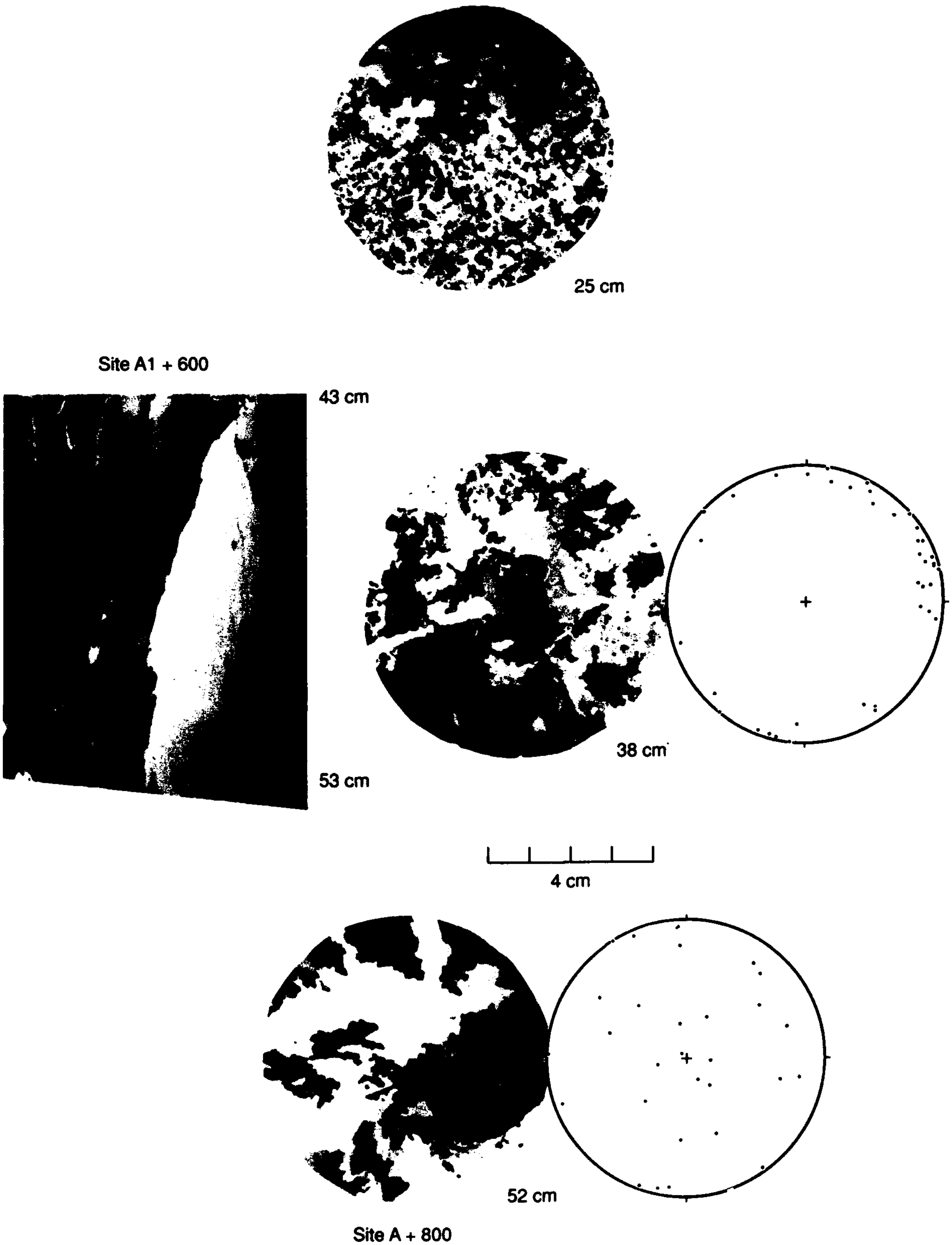


Figure 21 (cont'd).

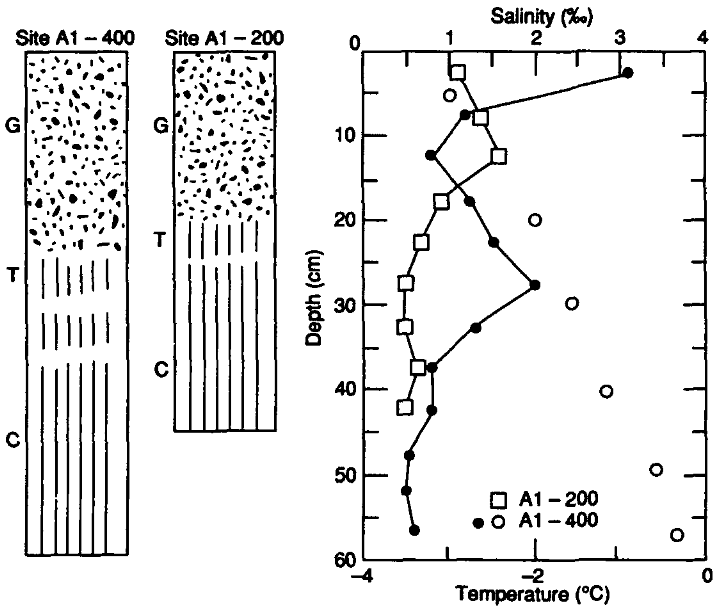


Figure 22. Vertical ice structure diagram, salinity profiles and temperature data from Sites A1–200 and A1–400 in the Intensive Study Area. The symbols are the same as in Figure 6.

region. With the exception of A1+800 the bottom congelation ice exhibited pronounced horizontal c-axis distributions. However, only at Site A1+200 was there any significant directional alignment of the c-axes within the horizontal plane. It would seem from the preponderance of granular ice at all four sites that, despite the level nature of the ice sheet in this part of the ISA, the earlier stages of growth occurred under somewhat less than quiet hydrodynamic conditions. This situation is also reflected in the highly variable nature of the salinity profiles within the granular ice component at all sites (Fig. 20). Only with the onset of congelation ice growth did the salinity variation decrease in a manner indicative of relatively quiet freezing. The occurrence of plainly visible dendritic structures in bottom ice at at least two sites, A1+600 and A1+200, indicates that congelation ice growth was still actively taking place at the time of coring.

Sites A1–200 and A1–400

Ice from these two sites along the line running approximately northeast from A1 was also sampled (Fig. 19). Both these sites were located on level ice with a 3- to 10-cm-thick snow cover. The salinity of the underlying water measured 3.8‰ at Site A1–200, essentially the same value as that measured beneath the ice at the *Aranda*.

As indicated in Figure 22, ice at both locations consisted of the sequence of granular, transition and congelation, with the granular component being much less dominant than at Sites A1 to A1+800. The unusually high salinity in the near surface layer of ice at Site A1–200 is consistent with an episode of flooding of snow by brackish water and subsequent refreezing. The temperature profile was essentially linear at Site A1–400.

The textural characteristics of ice at both sites are shown in Figure 23. The relatively coarse-grained nature of the columnar congelation ice is evident. At Site A1–200 a platelet structure was plainly visible in the bottom ice, indicating that congelation ice was still actively accreting at this location. The c-axes had become distributed in girdle-like fashion around the horizontal, but there was no significant directional alignment of axes within the horizontal plane.

The salinity profile from site A1–400 displayed somewhat more variability than the Site A1–200 profile. However, within the congelation ice component at both sites this variability substantially disappeared.

Additional cores were drilled at both sites for determining density variations in the ice. Densities ranged from 0.860 Mg/m^3 in bubbly granular ice to 0.915 Mg/m^3 in congelation ice.

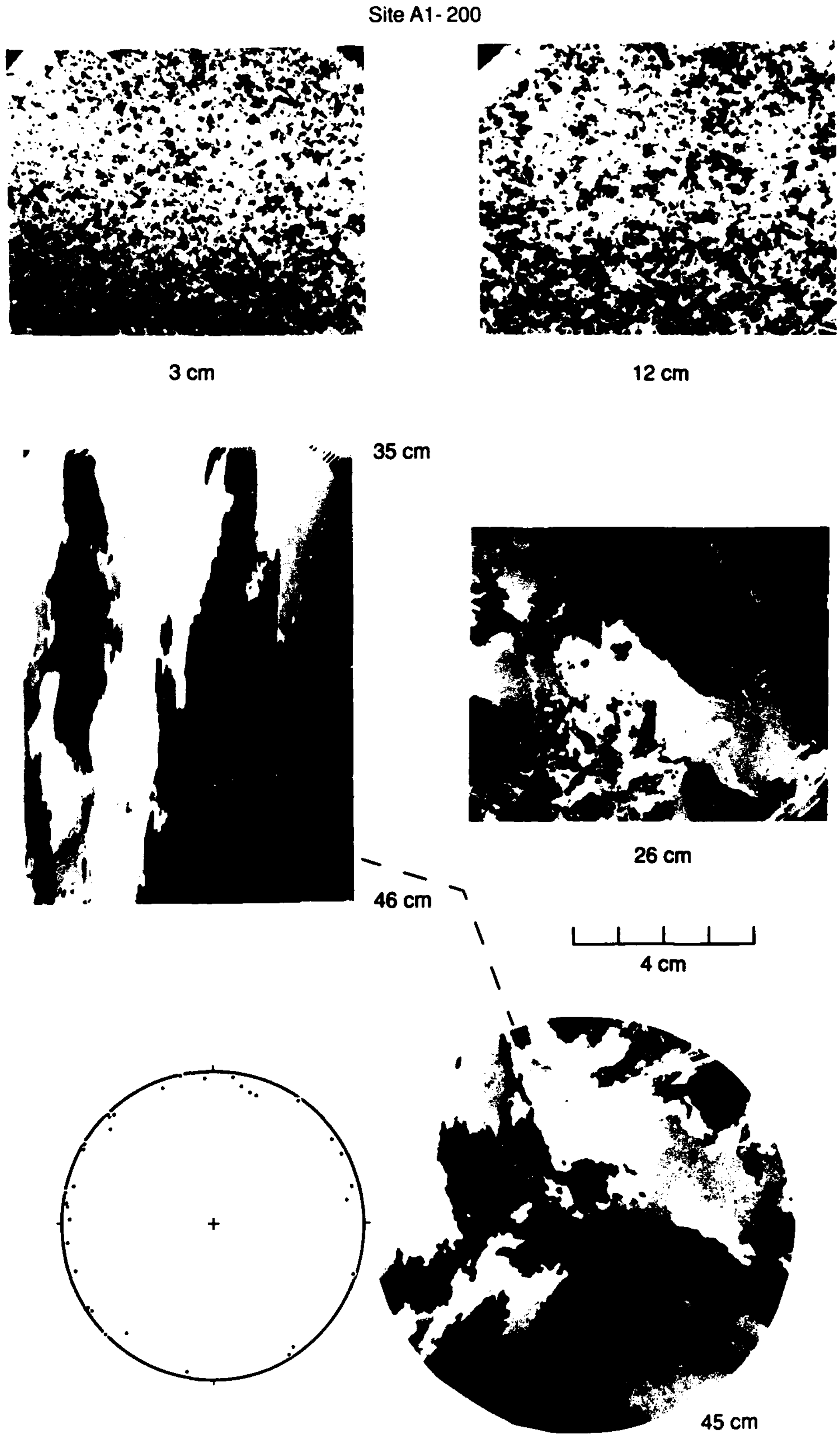


Figure 23. Vertical and horizontal thin-section photographs of ice structure and the c-axis fabric of bottom ice at Sites A1–200 and A1–400.

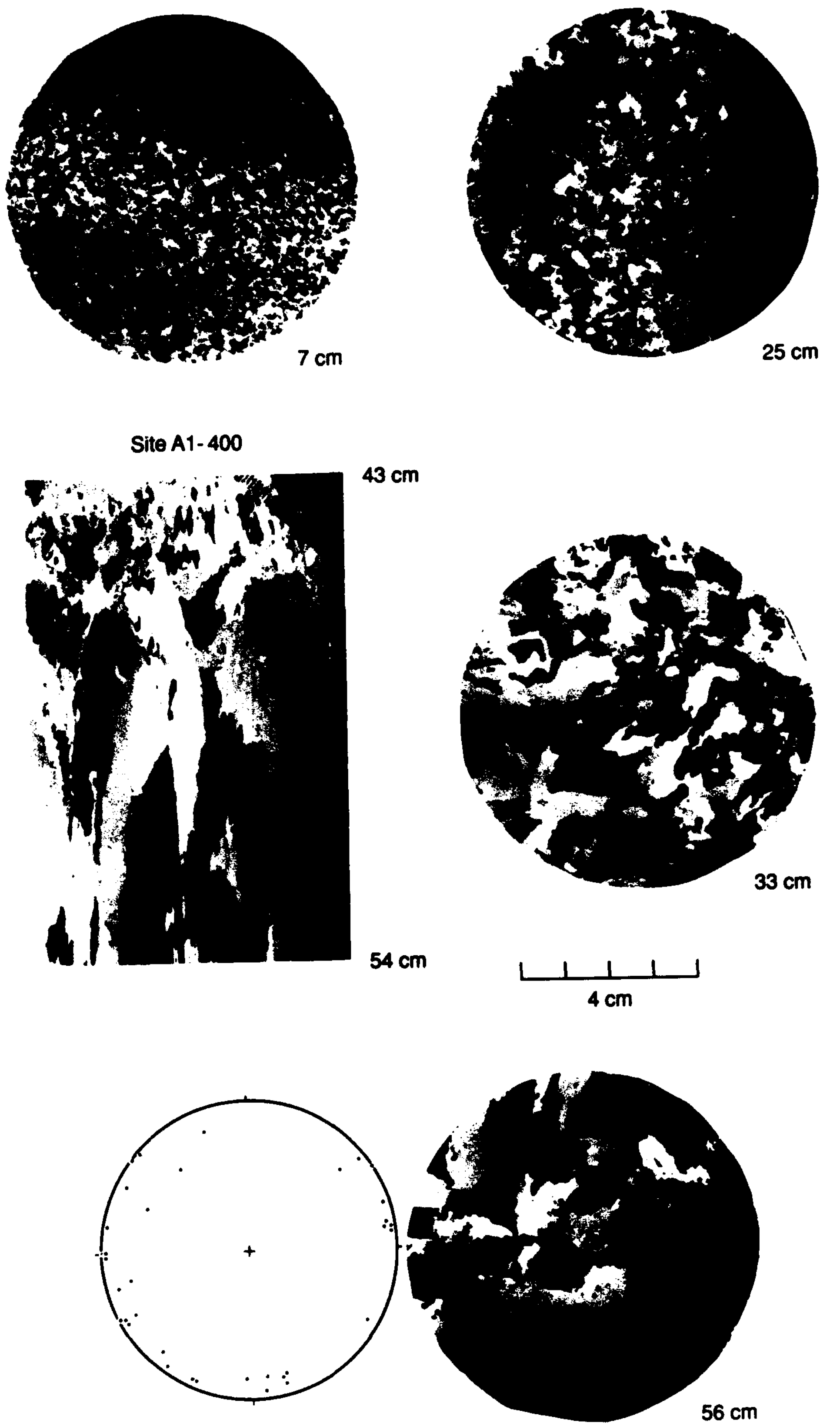


Figure 23 (con't). Vertical and horizontal thin-section photographs of ice structure and the c-axis fabric of bottom ice at Sites A1–200 and A1–400.

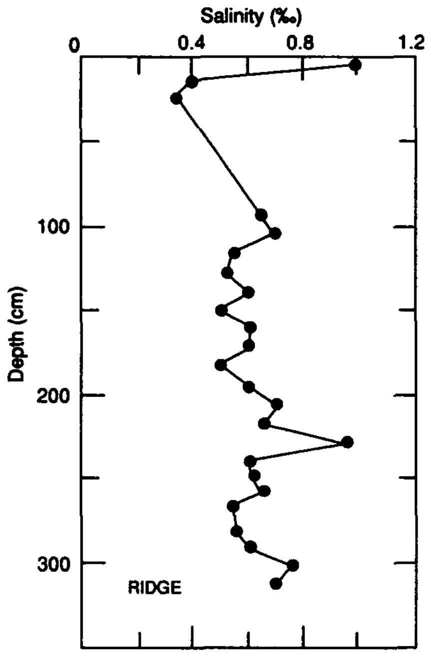


Figure 24. Salinity profile from a small pressure ridge located near the RV Aranda.

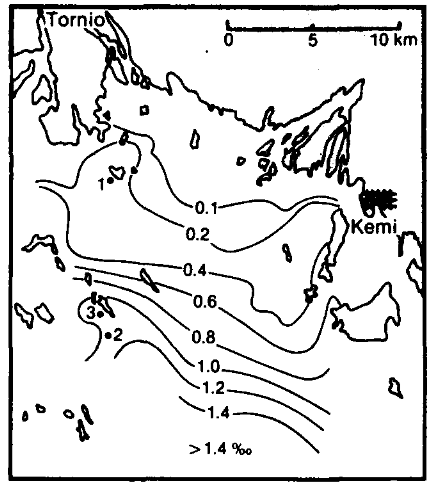


Figure 25. Sea surface salinity map for the northern portion of the Bay of Bothnia, 9–15 June 1959, from unpublished data of I. Hela (Palosuo 1961).

Ridge study

Studies were also made on a 3-m-long core from a pressure ridge (with a sail height of 1.5 m) located near the *Aranda*. The ridge was composed of blocks of granular (frazil) ice generally measuring less than 20 cm thick. Salinities ranged from 0.3–1.0‰ in the top meter of the ridge to between 0.5 and 0.95‰ in the lower 2 m (Fig. 24). The salinity profile is similar in form to that observed in ridges in the Arctic (Weeks et al. 1971). However, salinities were generally much lower in the Bay of Bothnia ridge. A more detailed account of the properties of this ridge is presented by Kankaanpä (1990).

Group D

After the completion of the formal BEPERS'88 exercise, additional investigations were undertaken south of the Finnish Coast Guard Station at Röyttä, located south of Tornio on the coast close to the Finnish–Swedish border at the north end of the Bay of Bothnia. The reason for sampling ice in this region was two-fold: to study ice on both sides of the planar/nonplanar interface transition that is believed to occur at a water salinity of approximately 1‰ (Weeks and Lofgren 1967), and to provide at least limited ground truth for the SAR imagery that had been obtained for this area during the regular BEPERS'88 overflights. Figure 25 shows an isosalinity map of the region based on data collected during the late spring of 1959 (Palosuo 1961). As there are no equivalent under-ice salinity data available for March, this map was used in selecting the sampling sites. As it turned out, our anticipated objective of examining the ice on either side of the dendritic/planar ice interface transition was not realized because the water beneath the sampling sites (Table 1) proved much less saline than indicated by the late spring data shown in Figure 25.

We were able to obtain a hard copy of the SAR image of the area of interest prior to the field sampling, allowing us to select sampling sites that gave both high and low radar returns. Sampling was carried out by snowmobile with navigation furnished by members of the Finnish Coast Guard.

Three sites were sampled at the locations shown in Figure 26. Two sites, T1 and T2, were located on fast ice in regions that yielded low radar returns. The third site, T3, was located on ice with a significantly stronger return. In addition the ice in this general region was thicker (68–87 cm) than in the area around the *Aranda* because of earlier freeze-up, and it was overlain by much thicker snow (38–52 cm). The snow was thick enough to obscure all

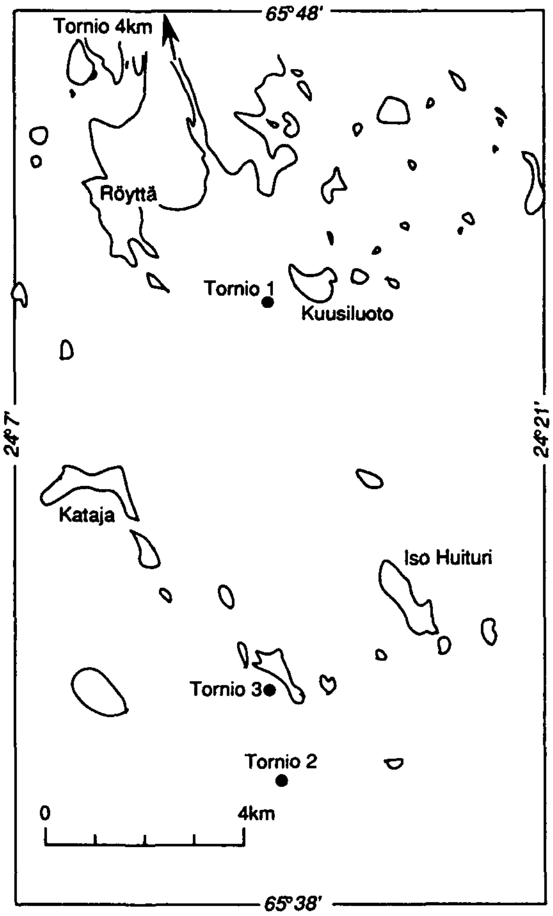


Figure 26. Sampling Sites T1, T2 and T3 relative to islands located south of Tornio, Finland.

but the largest surface roughness features. It also depressed the ice sheet sufficiently to create large negative freeboards of up to 6 cm.

The ice at the low-radar-return sites, T1 and T2, consisted entirely of congelation ice that exhibited structural characteristics very similar to those typifying lake ice. Some representative sections and c-axis plots from Site T2 are presented in Figure 27. Grain sizes varied from a few millimeters in the topmost part of the ice to dimensions larger than a thin-section slide (10 cm). The orientations of crystals at 2 cm were random. However, by 56 cm most crystals had become oriented with their c-axes horizontal. These features are by themselves not unusual, as large grain size increases with depth are common in lake ice. Also the orientations are in agreement with the observations of Gow (1986) that the growth of temperate lake ice sheets with a dominantly columnar crystal texture leads invariably to horizontal c-axes lower in the ice sheet. Another feature of the ice at Sites T1 and T2 was the absence of gas bubbles, giving the ice at these locations a distinctive glass-like appearance. This is unusual in that the great majority of lake ice sheets, temperate as well as polar, usually contain abundant inclusions of air, occurring in layers with shapes ranging from spherical to tubular (Swinzow 1966, Gow and Langston 1977). We can only speculate on the reasons for this lack of included gas. Perhaps it is the result of a chemically reducing aqueous environment in the river water that originates in extensive peatbog regions and also receives the effluvium from large wood pulp plants and wastes from a steel factory, coupled with poor reaeration caused by the presence of an impermeable ice cover.

No obvious substructure related to brine pocket formation was identified in any of the ice from the Tornio sites. Even so, a substructure, which to the unaided eye could have been mistaken for substructures observed in normal sea ice, could be seen on the bottom of blocks removed from the ice sheet (Fig. 28). Because of the later loss of these samples due to a refrigeration failure, we were unable to examine these features with a microscope. There would appear to be three possibilities for the occurrence of the bottom ice substructure: it is indeed a "low-salinity" version of the classical sea ice substructure resulting from a nonplanar growth interface or we could be seeing Forel striations (the surface manifestations of Tyndall figures [Ragle 1963]) or it could represent thermal or solution etching of the basal plane structure within individual ice crystals that averaged 8 cm^2 in cross section. The etch patterns evident in Figure 28 consisted of a groove and ridge structure; ridge to ridge widths averaged about 1 mm. The observation that the water salinities beneath the ice (~0.04‰) are far lower than those believed necessary to induce a nonplanar interface growth (~1.0‰), plus the fact that the measured water temperature at Site T2 was +0.4°C, clearly favors the latter two possibilities.

Structurally the ice at the site giving the high radar return (T3) was found to be radically different from that observed at Sites T1 and T2. It contained no congelation ice whatsoever and consisted of what appeared to be granular ice in the top few centimeters followed by transition ice that persisted all the way to the bottom of the 73-cm-thick ice sheet. Ice from top to bottom of the sheet was also characterized by an abundance of rounded bubbles up to 5 mm in diameter (Fig. 29). The ice

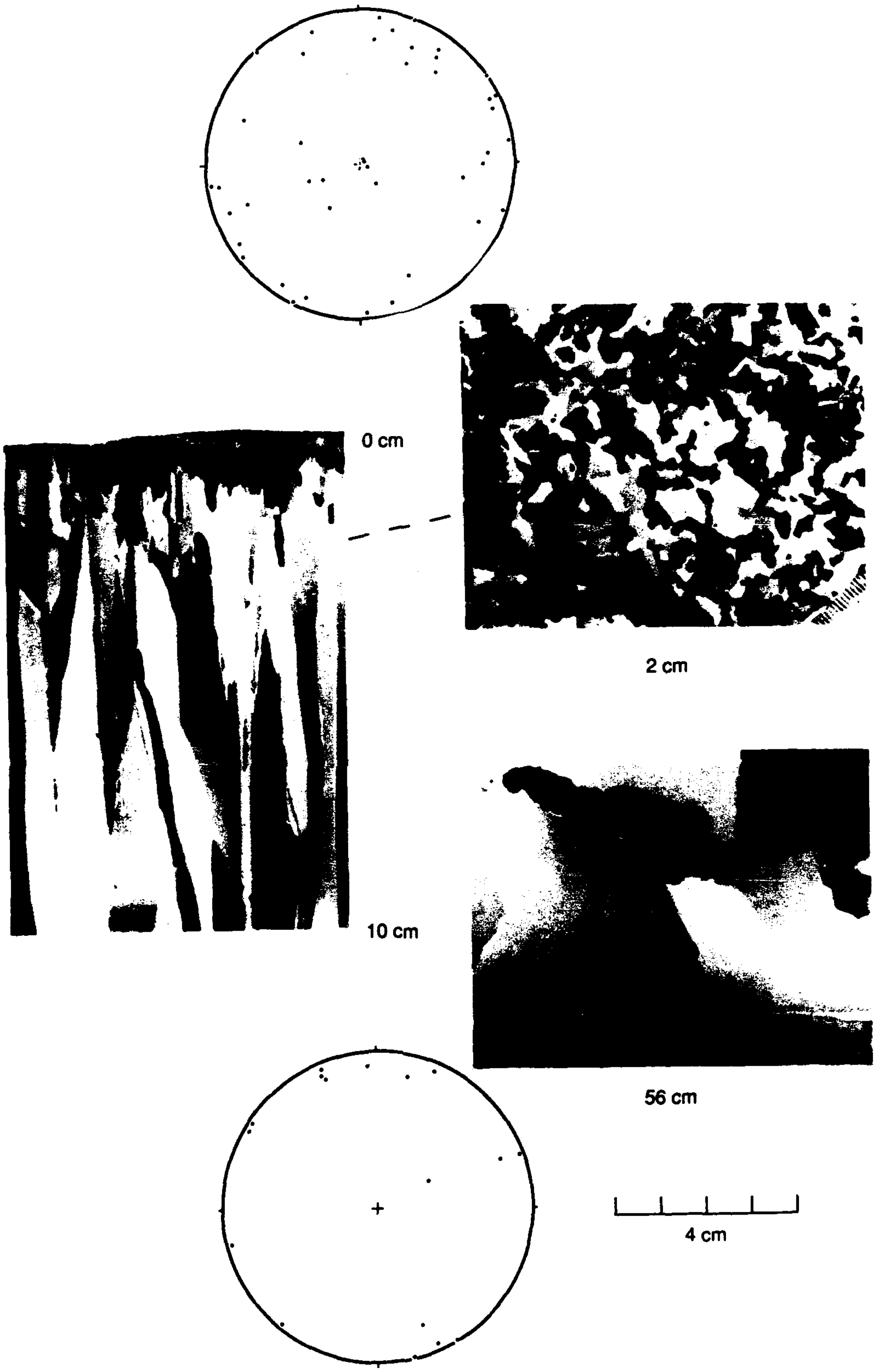


Figure 27. Vertical thin-section photograph of the top 10 cm and horizontal thin-section photographs of ice structure and the c-axis fabric of bottom and top ice at Site T2.

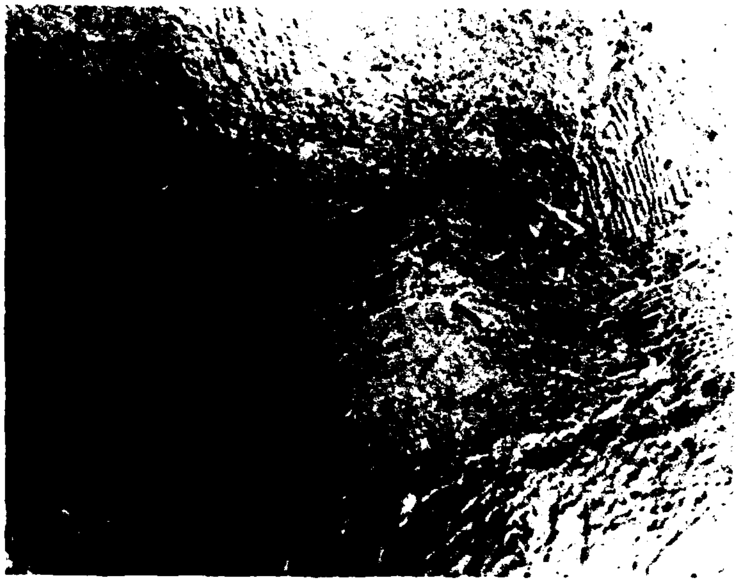


Figure 28. Photograph at natural scale of the substructure visible on the bottom of the ice sheet at Site T2 near Tornio.

Figure 29. Vertical thick section of ice at Site T3, photographed in reflected light to show the bubbly nature of the ice at this location. Note also near the top of the section the outline of part of an inclined block of ice.

Figure 30. Irregular upper surface of the ice sheet at Site T3 as revealed after removing the hard-packed snow cover.

was overlain by a very thick snow cover (52 cm) that effectively masked the presence of a rough, blocky upper surface, individual blocks measuring as much as 40 cm across (Fig. 30). Some idea of the chaotic crystal textures exhibited by the ice at Site T3 is indicated in the series of horizontal thin-section photographs shown in Figure 31. C-axis plots showed no systematic pattern of orientation.

Figure 32 shows the salinity profiles of the three Tornio sites as calculated from the conductivity of the meltwater. Sites T1 and T2 have salinities less than 0.1‰, with the exception of the upper sample from Site T2, whose salinity is just below 0.4‰. The ice above 40 cm at Site T3 was surprisingly saline, reaching a maximum value in the uppermost layer of more than 3‰. Initially this unusual salinity profile was thought to be produced by saline near-surface water, as a stable, low-density layer of river water developed beneath the fast ice cover. However, a more likely explanation is that the upper 40 cm of ice at Site T3 actually formed in another, more saline area of the Bay of Bothnia and was subsequently driven shoreward as brash ice where, once it became stabilized against the island near Site T3, it continued to accrete low-salinity, transition-type ice but not congelation ice.

Somewhat tantalizing, however, is the observation that the salinity of the water underlying the ice at all three Tornio sites, on the order 0.04 ‰, is significantly lower than that of the bulk ice itself. Normally congelation ice contains a lower content of dissolved ions than the water from which it froze. This doesn't appear to be the case here. Since we have no reason to suspect errors in our measurements, we can only conclude that the water underlying the ice at the Tornio sites had undergone a recent "freshening."

There are several reasons for the differences in the strength of the radar returns between Sites T1 and T2 (low returns) and Site T3 (high return). As mentioned, because of the continuous, deep snow cover, all sites initially appeared to be identical when viewed from above. However, removal of the snow showed that both of the low-return sites (T1, T2) had flat, smooth upper surfaces. This, when coupled with their flat, smooth ice/water interfaces and a lack of cylindrical gas inclusions that are known to act as forward scatterers in studies of arctic lakes (Weeks et al. 1978), should result in a strong bistatic radar return but a weak return to the transmitter site, as was observed. The ice at Site T3, on the other hand, possessed a very

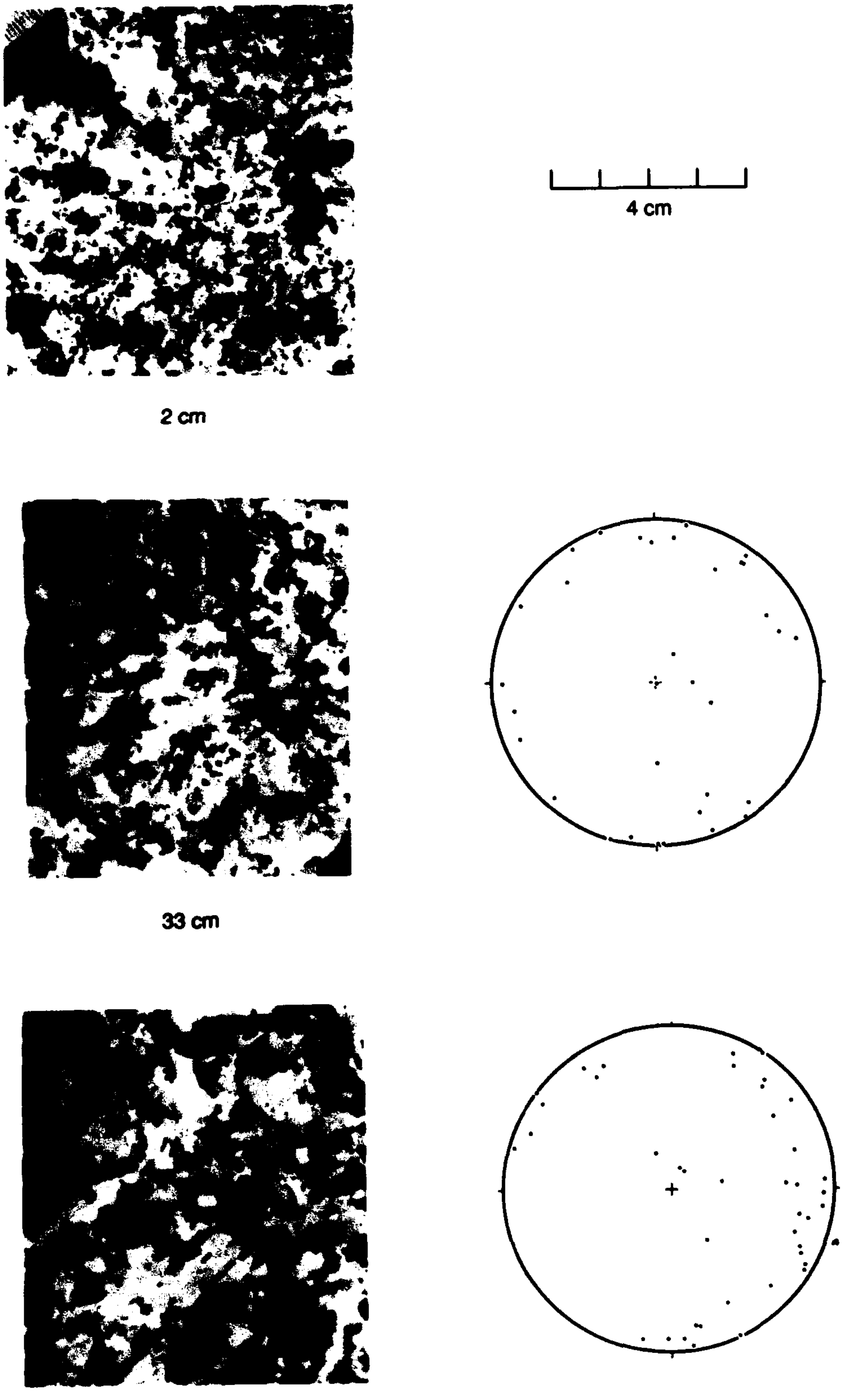


Figure 31. Selected horizontal thin-section photographs and the c-axis fabrics of ice at Site T3 near Tornio.

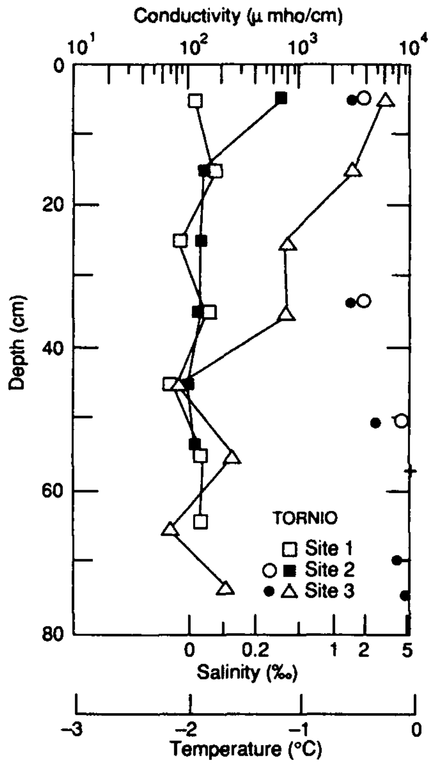


Figure 32. Salinity profiles from the three Tornio sites showing both the conductivities and the calculated equivalent salinities, assuming that the ionic ratios in the ice are the same as in standard sea water.

rough, blocky upper surface (Fig. 29), which should result in significant, nondirectional surface scattering. Also the ice at Site T3 contained a large number of spherical gas inclusions that would serve as volume scatterers. All these factors would tend to return an enhanced signal to the receiver site over that observed at Sites T1 and T2.

Comparisons of the BEPERS'88 data set with earlier observations of the structure and salinity characteristics of ice in the Bay of Bothnia revealed no major differences in these properties. Omstedt (1985) reported that the 1983–84 winter in the Bay of Bothnia was both warmer and windier than normal, leading to conditions that should favor the formation of frazil and mixed frazil–congelation ice types. This in fact was observed, with granular and mixed granular–columnar ice dominating the structure at six of the twelve sites examined by Omstedt. Columnar–congelation ice was predominant at the remaining six sites. These data are not too different from observations made during BEPERS'88, when ice at six of the sixteen sites were dominantly congelation in nature and seven of the remaining ten sites were dominated by granular ice (Table 2). However, bulk salinities reported by Omstedt were generally lower than those measured during BEPERS'88, ranging from 0.75 to 0.37‰ at Omstedt's sites compared to 1.21 to 0.58‰ at the BEPERS'88 sites. These differences can probably be attributed to the fact that Omstedt's coring sites were located about 100 km north of the *Aranda*. Based on data shown in Figures 3 and 4 of this report, Omstedt's sites would have been located over water with salinities of 3 to 3.5‰ compared to about 4‰ in the vicinity of the *Aranda*.

Conditions during the following winter (1984–85) were much colder and less dynamic when Leppäranta (1987) conducted ice structure and salinity measurements in the same general area as Omstedt's sites. During the 1984–85 winter the entire Gulf of Bothnia became completely ice covered during February. At the core site featured in Leppäranta's (1987) report, the ice sheet was 63 cm thick and consisted of 5–8 cm of frazil ice overlying 55–58 cm of congelation ice. The columnar ice component thus represents about 84–91% of the total ice thickness. This would be consistent with rapid freeze over and sustained congelation ice growth under conditions of very low dynamic activity. During March, ice in the northern Bay of Bothnia near Tornio reached a thickness of 122 cm (Leppäranta 1987), the thickest ever recorded in the Baltic Sea. Surface water salinities and the salinity profile of the ice measured by Leppäranta were very similar to those observed near Tornio during BEPERS'88. Apparently higher surface salinities existed at the time of Leppäranta's investigations than was the case when Omstedt examined ice in the same general area a year earlier. Some of the increased bulk salinity reported by Leppäranta may also have been incurred by greater rates of freezing induced by the much lower air temperatures that prevailed during the 1984–85 winter.

DERIVED ICE PROPERTIES

Here we examine the attenuation coefficient, the tensile strength and the elastic modulus profiles that would be expected for ice near the *Aranda* site and at Tornio. We then compare these values with profiles expected from more typical arctic sea ice. First-year sea ice properties are commonly estimated by developing correlations between the particular property of interest and the volume of liquid

brine in the ice. The variation in the attenuation coefficient κ as a function of brine volume V_b is based on the experimental measurements at 10 GHz (X-band) obtained by Hallikainen et al. (1988) on the 1987 BEPERS Pilot Study in the Gulf of Bothnia. The tensile strength σ_t and elastic modulus E_{eff} correlations are based on studies by Dykins (1970) and Vaudrey (1977). The appropriate equations are as follows:

$$\kappa\,(\mathrm{dB/m}) = 4.821 + 6.0893\,V_b - 0.02468\,V_b^2 + 3.24158 \times 10^{-5}\,V_b^3$$

$$\sigma_t\,(\mathrm{MPa}) = 0.816\left[1 - \sqrt{\frac{V_b}{140.4}}\right]$$

$$E_{eff}\,(\mathrm{GPa}) = 5.31\left[1 - \sqrt{\frac{V_b}{148.3}}\right]$$

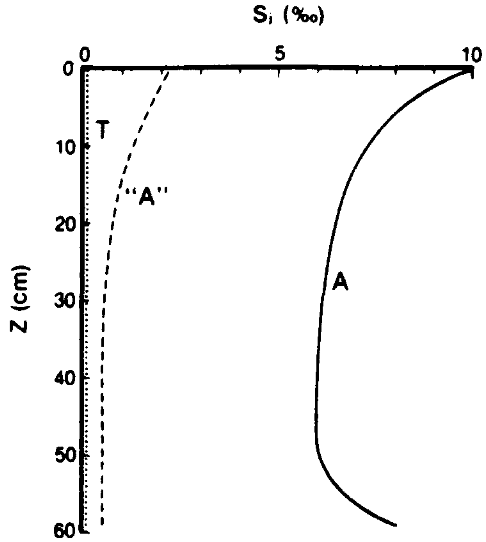


Figure 33. Salinity profiles assumed to be representative of 60-cm-thick ice near Tornio (T), near the RV Aranda *("A") and in the Arctic (A).*

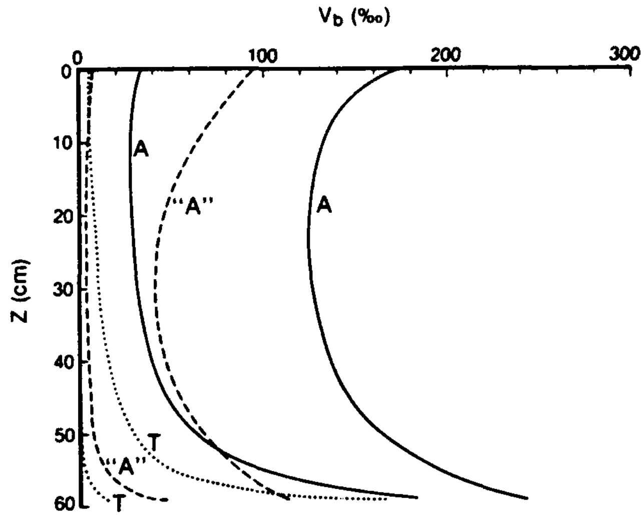


Figure 34. Brine volume profiles corresponding to the salinity profiles shown in Figure 33 and two temperature profiles described in the text. (T = Tornio, "A" = Aranda *and A = Arctic.)*

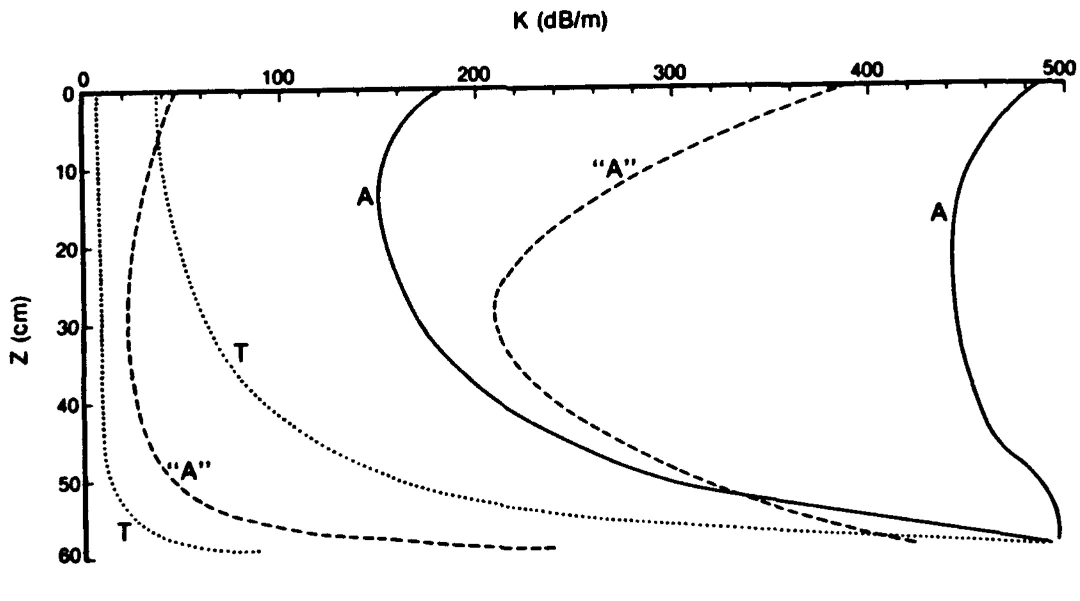


Figure 35. Calculated attenuation profiles corresponding to the brine volume profiles given in Figure 34 and the 10-GHz attenuation measurements of Hallikainen et al. (1988).

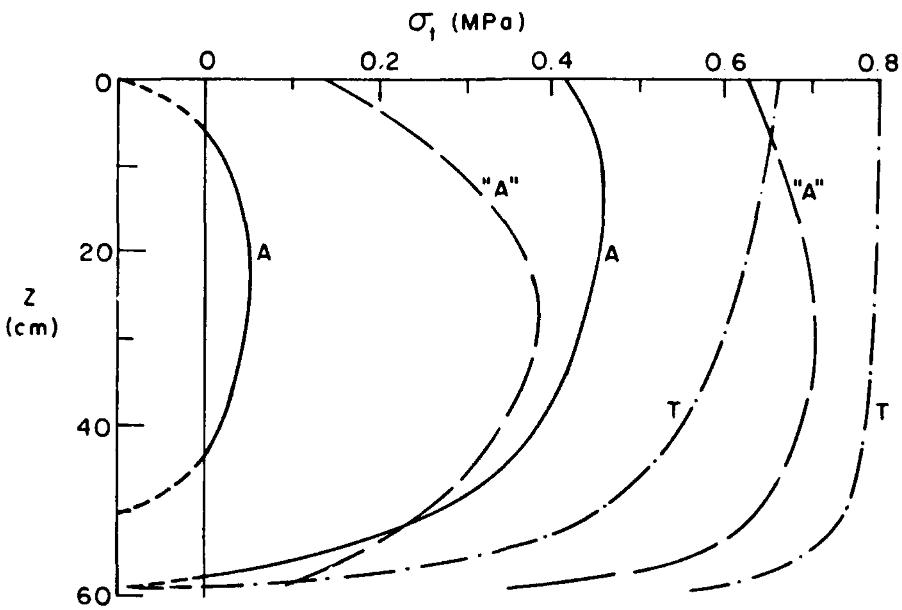


Figure 36. Calculated tensile strength profiles corresponding to the brine volume profiles given in Figure 34 and the tensile strength measurements of Dykins (1970).

where the brine volume V_b is expressed in parts per thousand.

The three salinity profiles that were used are shown in Figure 33. The Bothnian salinity and temperature profiles are "synthetic," with values selected to give a representative picture of the cores obtained from the different sampling areas (e.g. the Tornio area is represented by a profile in which the salinity has a constant value of 0.1‰). The arctic salinity values are taken from Cox and Weeks (1988, App. B, profile SG5E-31). The ice at all sites is taken to be 60 cm thick. The temperature profiles are assumed to be linear, with ice/snow interface temperatures of –1.2° and –1.0°C near the *Aranda* and at Tornio, respectively. A comparable "warm" ice surface temperature for the Arctic was taken to be –2.8°C. This corresponds to placing a temperature gradient of 1°C per 60 cm across the ice. In considering temperatures more typical of the Arctic, the surface temperature for all three profiles was taken to be –20°C. Figure 34 shows the brine volume profiles corresponding to the different salinity and temperature profiles. In each pair the profile with the higher brine volume corresponds to the higher ice temperature experienced in the Bay of Bothnia during BEPERS'88. Figures 35 and 36 show the corresponding κ and σ_t profiles (the E_{eff} profiles are generally similar to the σ_t profiles). Note that Figure 36 indicates negative strength values for parts of several profiles. This simply indicates that the strength–brine volume correlations used are inadequate to represent the Bothnian data at near-melting temperatures (in the range of large brine volumes). Test sets specific to the Bothnian ice are clearly needed. Figure 37 shows the cumulative one-way loss for the three salinity profiles

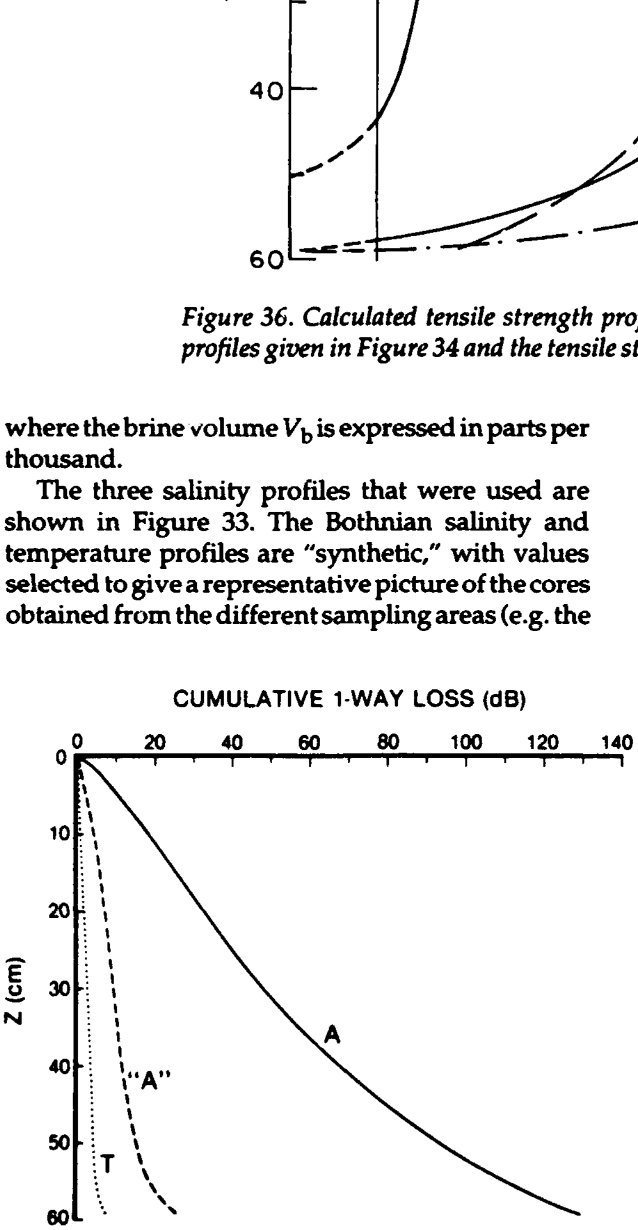


Figure 37. Cumulative one-way loss at normal incidence corresponding to the brine volume profiles given in Figure 34 assuming an ice surface temperature of –20°C. (T = Tornio, "A" = Aranda and A = Arctic.)

assuming an ice surface temperature of –20°C. In the arctic profile, a 5-dB loss has occurred at 4 cm; in the *Aranda* profile the same loss occurred at 15 cm and at Tornio at 55 cm.

CONCLUSIONS

Surface truth observations made during the BEPERS'88 remote sensing experiment in March 1988 included detailed measurements of snow and ice thickness, temperature, salinity and structure profiles and c-axis fabrics in the different types of brackish ice that had formed in the Bay of Bothnia. Both relatively undeformed fast ice and ice that had formed under more disturbed conditions were sampled. Ice thicknesses varied from 36 to 64 cm in the bay east of Umeä, Sweden, with somewhat thicker ice (up to 76 cm) occurring in the northernmost areas of the Bay of Bothnia, near Tornio. The snow cover on the ice near Tornio also was much thicker than elsewhere, varying from 25 to 52 cm, compared to thickness ranging from a trace to 22 cm at other locations. Because of the mild weather at the time of the experiments, minimum temperatures in the ice usually measured higher than –3.5°C.

Three major ice crystal types were identified—granular, transition and columnar—with the amounts of each varying with location and depending to a large extent on the level of disturbance in the water column. At seven of the sixteen sites investigated structurally, granular ice was the dominant component. In all cases it consisted of refrozen water-soaked snow or consolidated frazil or both, and it was restricted to the top of the ice sheet. At most sites it was directly underlain by transition ice that often combined the properties of granular and columnar ice; at some locations it appeared to result from oscillation in growth of the two ice crystal types. It often displayed irregular horizontal layering. The presence of short, vertically elongated crystals at the bottom of some transition layer probably signals the onset of columnar congelation ice growth. Only at one location was transition ice the dominant component. At another site it occurred in about equal proportions with congelation ice to make 86% of the ice sheet thickness.

At six of the sixteen sites examined for structure, columnar congelation ice was the predominant ice crystal type. At all but two of the sixteen sites the bottom ice consisted of congelation ice, which in many cases exhibited the ice plate–brine layer crystal substructure that is so typical of arctic sea ice. At two sites where this structure was especially well developed, plate widths of 0.7–0.8 mm were measured. These are very similar to the spacings observed in arctic sea ice at a similar stage of growth. Two of the Tornio sites consisted entirely of congelation ice formed from the freezing of fresh riverine water. This of course precluded the formation of a sea ice substructure. However, unmistakable evidence of a platelike substructure was observed in bottom ice at one of the Tornio sites. Its origin is attributed to thermal or solution etching of the basal plane structure within individual crystals of ice.

A variety of c-axis fabrics were observed in the congelation ice, including random, vertical and horizontal (planar) orientations. Aligned c-axes were observed at a number of sites, but a lack of current meter data precluded any direct correlation of such alignments with the current direction at the ice/water interface. However, at one site located in a channel between two islands, the c-axis orientation closely paralleled the inferred direction of flow of water between the two islands.

Surface water salinities ranged from 3.6 to 4.1‰ except for the northernmost sites near Tornio, where essentially fresh water of riverine origin was present. Bulk salinities ranged from 1.21–0.58‰ in the area of the main experiment to as low as 0.06‰ in ice near Tornio. The ratio of salt retained by the ice to that present in the parent water is about 1:4, a ratio very similar to that observed in young arctic sea ice (8‰ bulk salinity) relative to the arctic ocean (34‰ salinity).

At the three Tornio sites, surface roughness and physical characteristics of the ice were measured for direct correlation of these properties with imagery from SAR overflights. At Sites T1 and T2 a combination of bubble-free ice and smooth top and bottom surfaces resulted in a strong bistatic radar return but in no return to the receiver at the transmitter site. In the case of Site T3, however, the signal return to the receiver was much enhanced. Factors contributing to this enhanced signal return included the rough blocky upper ice surface causing significant nondirectional surface scattering, and the presence in the ice of large numbers of spherical bubbles resulting in significant volume scattering.

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13. ABSTRACT (*Maximum 200 words*)
Field observations made during the March 1988 BEPERS (Bothnian Experiment in Preparation for ERS-1) remote sensing experiment included measurements of the snow and ice thickness, temperature, salinity and crystal structure profiles of the different types of brackish ice that form in the Bay of Bothnia. Both undeformed fast ice and ice that had formed under more disturbed conditions were sampled. Ice thicknesses varied from 36 to 64 cm in the bay to the east of Umeå, Sweden, with somewhat thicker ice (76 cm) occurring in the northernmost, nearly fresh water areas of the Bay of Bothnia. Three major ice crystal types or textures were identified—granular, transition and columnar ice—with the amount of each depending on the level of disturbance in the water column. At seven of the sixteen sites investigated, granular (mainly frazil) ice was the dominant component. At six of the remaining nine sites, columnar–congelation ice was the predominant ice crystal type. A mix of transition and transition–congelation ice types dominated the structure of the remaining three sites. At all but two sites the bottom ice consisted of congelation ice, which in many instances exhibited the ice plate and brine layer substructure so typical of arctic sea ice. A variety of c-axis fabrics were observed in the columnar–congelation ice, including random, vertical and horizontal (planar) orientations. Aligned c-axes were observed at several locations, but in most cases there was no obvious pattern to the geographic arrangement of these fabrics. Surface water salinities ranged from 3.6 to 4.1‰ except at the northernmost sites near Tornio, where essentially riverine fresh water was present. Bulk

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salinities ranged from 1.21–0.58‰ in the area of the main experiment to as low as 0.06‰ near Tornio. Ice temperatures were usually higher than –3.5°C. Brine volume profiles were used to estimate representative ice property profiles for comparison with those of more typical sea ice of similar thicknesses from the Arctic Ocean. A variety of structural factors contributing to specific areas of high and low radar return from ice in the Bay of Bothnia are also discussed.

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